

PHOTOGRAPH THIS SHEET

AD A129295

DTIC ACCESSION NUMBER



LEVEL



INVENTORY

"Thermophysical Properties of Selected Aerospace Materials. Part II: Thermophysical Properties of Seven Materials"

DOCUMENT IDENTIFICATION

1977

DISTRIBUTION STATEMENT A

Approved for public release
Distribution Unlimited

245 P

DISTRIBUTION STATEMENT

ACCESSION FOR	
NTIS	GRA&I
DTIC	TAB
UNANNOUNCED	
JUSTIFICATION	
BY	
DISTRIBUTION /	
AVAILABILITY CODES	
DIST	AVAIL AND/OR SPECIAL
A	21

DISTRIBUTION STAMP



DATE ACCESSIONED



83 05 18 019

DATE RECEIVED IN DTIC

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-DDA-2

**THERMOPHYSICAL PROPERTIES OF
SELECTED AEROSPACE MATERIALS**

**PART II: THERMOPHYSICAL PROPERTIES OF
SEVEN MATERIALS**

AD A 29290

THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS CENTER
CINDAS - Purdue University

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) "Thermophysical Properties of Selected Aerospace Materials. Part II: Thermophysical Properties of Seven Materials"		5. TYPE OF REPORT & PERIOD COVERED Data Book (See block 18)
7. AUTHOR(s) Touloukian, Y. S. and Ho, C. Y.		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS CINDAS/Purdue University 2595 Yeager Road West Lafayette, IN 47906		8. CONTRACT OR GRANT NUMBER(s) DSA 900-77-C-37758
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Logistics Agency DTIC-AI/Cameron Station Alexandria, VA 22314		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Army Materials & Mechanics Research Center Attn: DRXMR-P/Arsenal Street Watertown, MA 02172		12. REPORT DATE 1977
		13. NUMBER OF PAGES 242
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES TEPIAC Publication (DTIC Source Code 413571) Limited hard copies on Data Book available from TEPIAC (see block 9 above). Discounted price: \$15.00 Microfiche copies available from DTIC		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) *Thermal Conductivity--*Specific Heat--*Heat of Fusion--*Thermal Linear Expansion--*Thermal diffusivity--aluminum alloy 2024--AISI 304 stainless steel--Pyroceram--Silicon nitride--Carbon fiber epoxy composite--Glass fiber epoxy composite--Graphite fiber epoxy composite--Thermophysical properties		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This work presents the most comprehensively compiled experimental data and information on five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information. (continued on reverse side)		

20. ABSTRACT (Cont)

The five thermophysical properties are thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. The seven selected materials are aluminum alloy 2024, AISI 304 stainless steel, Pyroceram (Corning 9606), silicon nitride, boron fiber epoxy composite, glass fiber epoxy composite, and graphite fiber epoxy composite.

The experimental data and the recommended values for each property of each material are presented in both tabular and graphical forms, together with a discussion text and a specification table. The former reviews the available data and information, discusses the considerations involved in the data analysis and synthesis and in arriving at the final assessment and recommendation and specified the uncertainty of the recommended values, and the latter gives the information on the specimen characterization and measurement method and condition for each set of experimental data.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, the general background information on the behavior of each of the five thermophysical properties and on the procedures used for the data evaluation and the generation of recommended values is provided. A concise description of each of the seven selected materials is also given.

**THERMOPHYSICAL PROPERTIES OF
SELECTED AEROSPACE MATERIALS**

PART II: THERMOPHYSICAL PROPERTIES OF SEVEN MATERIALS

Y. S. TOULOUKIAN and C. Y. HO, Editors

**THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS CENTER
CINDAS - Purdue University**

Notice: This volume may be procured from:

**TEPIAC/CINDAS
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906**

Copyright © 1977 by the Purdue Research Foundation, West Lafayette, Indiana 47907

All rights reserved. This work or any part thereof may not be reproduced in any form without written permission of the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University.

PREFACE

This volume was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a DOD Information Analysis Center operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under Contract No. DSA900-76-C-0860 with the Defense Supply Agency (DSA), Alexandria, Virginia, with Mr. J. L. Blue (Hq. DSA) as the IAC Program Manager and Mr. Samuel Valencia (Army Materials and Mechanics Research Center) as the Contracting Officer's Technical Representative.

The overall program is aimed at providing data and information on all the important thermophysical properties of selected aerospace materials. The effort in the last year was concentrated on the thermal radiative properties (hemispherical, normal, and angular spectral emittance, reflectance, absorptance, and transmittance) of twenty-seven selected aerospace materials, resulting in the publication entitled "Thermophysical Properties of Selected Aerospace Materials. Part I: Thermal Radiative Properties," copies of which are available from TEPIAC/CINDAS. The effort in the current year has been concentrated on five other thermophysical properties of seven materials, resulting in this volume which constitutes Part II of this series of publications.

This special project has been carried out by a team of TEPIAC staff, with the following individuals in responsible charge:

Dr. P. D. Desai -- Specific Heat, Heat of Fusion, and Thermal Linear Expansion

Dr. K. Y. Wu -- Thermal Conductivity and Thermal Diffusivity

It is hoped that this reference work will prove useful to a large technical community as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is felt that the critical evaluation, analysis and reference data recommendation, whenever possible, constitute perhaps the most unique aspect of this work.

In putting a volume of this magnitude together it is nearly impossible to avoid some errors and omissions. It is hoped that we were able to keep these to a minimum. The editors and contributors would be most grateful if those who use this work bring to their attention any additional known data or any possible errors that might have been inadvertently committed.

October 1976
West Lafayette, IN 47906

Y. S. TOULOUKIAN
Director of CINDAS
Distinguished Atkins Professor of
Engineering
Purdue University

SUMMARY

This work presents the most comprehensively compiled experimental data and information on five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information.

The five thermophysical properties are thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. The seven selected materials are aluminum alloy 2024, AISI 304 stainless steel, Pyroceram (Corning 9606), silicon nitride (Si_3N_4), boron fiber epoxy composite, glass fiber epoxy composite, and graphite fiber epoxy composite.

The experimental data and the recommended values for each property of each material are presented in both tabular and graphical forms, together with a discussion text and a specification table. The former reviews the available data and information, discusses the considerations involved in the data analysis and synthesis and in arriving at the final assessment and recommendation, and specifies the uncertainty of the recommended values, and the latter gives the information on the specimen characterization and measurement method and condition for each set of experimental data.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, the general background information on the behavior of each of the five thermophysical properties and on the procedures used for the data evaluation and the generation of recommended values is provided. A concise description of each of the seven selected materials is also given.

CONTENTS

	Page
PREFACE	iii
SUMMARY	iv
LIST OF TABLES	vii
LIST OF FIGURES	xi
1. INTRODUCTION	1
2. GENERAL BACKGROUND	2
2.1. Thermophysical Properties	2
2.2. Data Evaluation and Generation of Recommended Values	6
2.3. Presentation of Data	7
3. THERMOPHYSICAL PROPERTIES OF SELECTED MATERIALS	10
3.1. Aluminum Alloy 2024.	10
a. Thermal Conductivity	11
b. Specific Heat	19
c. Heat of Fusion	25
d. Thermal Linear Expansion.	26
e. Thermal Diffusivity	32
3.2. AISI 304 Stainless Steel.	37
a. Thermal Conductivity	37
b. Specific Heat	47
c. Heat of Fusion	52
d. Thermal Linear Expansion	53
e. Thermal Diffusivity	58
3.3. Pyroceram (Corning 9606)	63
a. Thermal Conductivity	63
b. Specific Heat	68
c. Heat of Fusion	72
d. Thermal Linear Expansion.	73
e. Thermal Diffusivity	77
3.4. Silicon Nitride (Si_3N_4)	82
a. Thermal Conductivity	82
b. Specific Heat	89
c. Heat of Fusion	93
d. Thermal Linear Expansion	94
e. Thermal Diffusivity	107
3.5. Boron Fiber Epoxy Composite.	111
a. Thermal Conductivity	111
b. Specific Heat	116
c. Heat of Fusion	120
d. Thermal Linear Expansion	121
e. Thermal Diffusivity	129

3.6. Glass Fiber Epoxy Composite	130
a. Thermal Conductivity	130
b. Specific Heat	143
c. Heat of Fusion	155
d. Thermal Linear Expansion	156
e. Thermal Diffusivity	176
3.7. Graphite Fiber Epoxy Composite	178
a. Thermal Conductivity	178
b. Specific Heat	185
c. Heat of Fusion	189
d. Thermal Linear Expansion	190
e. Thermal Diffusivity	216
4. REFERENCES	217

LIST OF TABLES

	<u>Page</u>
1- 1. Recommended Thermal Conductivity of Aluminum Alloy 2024	13
1- 2. Measurement Information on the Thermal Conductivity of Aluminum Alloy 2024	15
1- 3. Experimental Data on the Thermal Conductivity of Aluminum Alloy 2024	17
1- 4. Recommended Specific Heat of Aluminum Alloy 2024	20
1- 5. Measurement Information on the Specific Heat of Aluminum Alloy 2024	22
1- 6. Experimental Data on the Specific Heat of Aluminum Alloy 2024	23
1- 7. Recommended Thermal Linear Expansion of Aluminum Alloy 2024	27
1- 8. Measurement Information on the Thermal Linear Expansion of Aluminum Alloy 2024	29
1- 9. Experimental Data on the Thermal Linear Expansion of Aluminum Alloy 2024	31
1-10. Recommended Thermal Diffusivity of Aluminum Alloy 2024	33
1-11. Measurement Information on the Thermal Diffusivity of Aluminum Alloy 2024	35
1-12. Experimental Data on the Thermal Diffusivity of Aluminum Alloy 2024	36
2- 1. Recommended Thermal Conductivity of AISI 304 Stainless Steel	39
2- 2. Measurement Information on the Thermal Conductivity of AISI 304 Stainless Steel	41
2- 3. Experimental Data on the Thermal Conductivity of AISI 304 Stainless Steel	45
2- 4. Recommended Specific Heat of AISI 304 Stainless Steel	48
2- 5. Measurement Information on the Specific Heat of AISI 304 Stainless Steel	50
2- 6. Experimental Data on the Specific Heat of AISI 304 Stainless Steel	51
2- 7. Recommended Thermal Linear Expansion of AISI 304 Stainless Steel	54
2- 8. Measurement Information on the Thermal Linear Expansion of AISI 304 Stainless Steel	56
2- 9. Experimental Data on the Thermal Linear Expansion of AISI 304 Stainless Steel	57
2-10. Recommended Thermal Diffusivity of AISI 304 Stainless Steel	59

2- 11.	Measurement Information on the Thermal Diffusivity of AISI 304 Stainless Steel	61
2- 12.	Experimental Data on the Thermal Diffusivity of AISI 304 Stainless Steel	62
3- 1.	Recommended Thermal Conductivity of Pyroceram (Corning 9606) . . .	64
3- 2.	Measurement Information on the Thermal Conductivity of Pyroceram (Corning 9606)	66
3- 3.	Experimental Data on the Thermal Conductivity of Pyroceram (Corning 9606)	67
3- 4.	Provisional Specific Heat of Pyroceram (Corning 9606)	69
3- 5.	Measurement Information on the Specific Heat of Pyroceram (Corning 9606)	71
3- 6.	Experimental Data on the Specific Heat of Pyroceram (Corning 9606) . . .	71
3- 7.	Provisional Thermal Linear Expansion of Pyroceram (Corning 9606) . .	74
3- 8.	Measurement Information on the Thermal Linear Expansion of Pyroceram (Corning 9606)	76
3- 9.	Experimental Data on the Thermal Linear Expansion of Pyroceram (Corning 9606)	76
3- 10.	Recommended Thermal Diffusivity of Pyroceram (Corning 9606)	78
3- 11.	Measurement Information on the Thermal Diffusivity of Pyroceram (Corning 9606)	80
3- 12.	Experimental Data on the Thermal Diffusivity of Pyroceram (Corning 9606)	81
4- 1.	Recommended Thermal Conductivity of Silicon Nitride (Si_3N_4)	84
4- 2.	Measurement Information on the Thermal Conductivity of Silicon Nitride (Si_3N_4)	86
4- 3.	Experimental Data on the Thermal Conductivity of Silicon Nitride (Si_3N_4)	88
4- 4.	Recommended Specific Heat of Silicon Nitride (Si_3N_4)	90
4- 5.	Measurement Information on the Specific Heat of Silicon Nitride (Si_3N_4)	92
4- 6.	Experimental Data on the Specific Heat of Silicon Nitride (Si_3N_4)	92
4-7A.	Provisional Thermal Linear Expansion of Alpha Silicon Nitride ($\alpha\text{-Si}_3\text{N}_4$)	96

4-7B.	Provisional Thermal Linear Expansion of Beta Silicon Nitride (β - Si_3N_4)	97
4- 8.	Measurement Information on the Thermal Linear Expansion of Silicon Nitride (Si_3N_4)	103
4- 9.	Experimental Data on the Thermal Linear Expansion of Silicon Nitride (Si_3N_4)	105
4-10.	Recommended Thermal Diffusivity of Silicon Nitride (Si_3N_4)	108
4-11.	Measurement Information on the Thermal Diffusivity of Silicon Nitride (Si_3N_4)	110
4-12.	Experimental Data on the Thermal Diffusivity of Silicon Nitride (Si_3N_4)	110
5- 1.	Provisional Thermal Conductivity of Boron Fiber Epoxy Composites	113
5- 2.	Measurement Information on the Thermal Conductivity of Boron Fiber Epoxy Composites	115
5- 3.	Experimental Data on the Thermal Conductivity of Boron Fiber Epoxy Composites	115
5- 4.	Provisional Specific Heat of Boron Fiber Epoxy Composites	117
5- 5.	Measurement Information on the Specific Heat of Boron Fiber Epoxy Composites	119
5- 6.	Experimental Data on the Specific Heat of Boron Fiber Epoxy Composites	119
5- 7.	Provisional Thermal Linear Expansion of Boron Fiber Epoxy Composites	122
5- 8.	Measurement Information on the Thermal Linear Expansion of Boron Fiber Epoxy Composites	125
5- 9.	Experimental Data on the Thermal Linear Expansion of Boron Fiber Epoxy Composites	127
6- 1.	Typical Thermal Conductivity of Glass Fiber Epoxy Composite	132
6- 2.	Measurement Information on the Thermal Conductivity of Glass Fiber Epoxy Composites	134
6- 3.	Experimental Data on the Thermal Conductivity of Glass Fiber Epoxy Composites	140
6- 4.	Provisional Specific Heat of Glass Fiber Epoxy Composites	145
6- 5.	Measurement Information on the Specific Heat of Glass Fiber Epoxy Composites	150
6- 6.	Experimental Data on the Specific Heat of Glass Fiber Epoxy Composites	153

6- 7.	Provisional Thermal Linear Expansion of Glass Fiber Epoxy Composites	159
6- 8.	Measurement Information on the Thermal Linear Expansion of Glass Fiber Epoxy Composites	166
6- 9.	Experimental Data on the Thermal Linear Expansion of Glass Fiber Epoxy Composites	172
6-10.	Measurement Information on the Thermal Diffusivity of Glass Fiber Epoxy Composites	177
6-11.	Experimental Data on the Thermal Diffusivity of Glass Fiber Epoxy Composites	177
7- 1.	Provisional Thermal Conductivity of Graphite Fiber Epoxy Composites. .	180
7- 2.	Measurement Information on the Thermal Conductivity of Graphite Fiber Epoxy Composites	182
7- 3.	Experimental Data on the Thermal Conductivity of Graphite Fiber Epoxy Composites	184
7- 4.	Provisional Specific Heat of Graphite Fiber Epoxy Composites	186
7- 5.	Measurement Information on the Specific Heat of Graphite Fiber Epoxy Composites	188
7- 6.	Experimental Data on the Specific Heat of Graphite Fiber Epoxy Composites	188
7- 7.	Provisional Thermal Linear Expansion of Graphite Fiber Epoxy Composites	194
7- 8.	Measurement Information on the Thermal Linear Expansion of Graphite Fiber Epoxy Composites	200
7- 9.	Experimental Data on the Thermal Linear Expansion of Graphite Fiber Epoxy Composites	210

LIST OF FIGURES

	<u>Page</u>
1- 1. Thermal Conductivity of Aluminum Alloy 2024	14
1- 2. Specific Heat of Aluminum Alloy 2024	21
1- 3. Thermal Linear Expansion of Aluminum Alloy 2024	28
1- 4. Thermal Diffusivity of Aluminum Alloy 2024	34
2- 1. Thermal Conductivity of AISI 304 Stainless Steel	40
2- 2. Specific Heat of AISI 304 Stainless Steel	49
2- 3. Thermal Linear Expansion of AISI 304 Stainless Steel	55
2- 4. Thermal Diffusivity of AISI 304 Stainless Steel	60
3- 1. Thermal Conductivity of Pyroceram (Corning 9606)	65
3- 2. Specific Heat of Pyroceram (Corning 9606)	70
3- 3. Thermal Linear Expansion of Pyroceram (Corning 9606)	75
3- 4. Thermal Diffusivity of Pyroceram (Corning 9606)	79
4- 1. Thermal Conductivity of Silicon Nitride	85
4- 2. Specific Heat of Silicon Nitride	91
4-3A. Thermal Linear Expansion of Alpha Silicon Nitride Parallel to a-Axis	98
4-3B. Thermal Linear Expansion of Alpha Silicon Nitride Parallel to c-Axis	99
4-3C. Thermal Linear Expansion of Polycrystalline Silicon Nitride	100
4-3D. Thermal Linear Expansion of Beta Silicon Nitride Parallel to a-Axis	101
4-3E. Thermal Linear Expansion of Beta Silicon Nitride Parallel to c-Axis	102
4- 4. Thermal Diffusivity of Silicon Nitride	109
5- 1. Thermal Conductivity of Boron Fiber Epoxy Composites	114
5- 2. Specific Heat of Boron Fiber Epoxy Composites	118
5-3A. Longitudinal Thermal Linear Expansion of Boron Fiber Epoxy Composites	123

5-3B.	Transverse Thermal Linear Expansion of Boron Fiber Epoxy Composites	124
6- 1.	Thermal Conductivity of Glass Fiber Epoxy Composites	123
6-2A.	Specific Heat of E-Glass Fiber DER-332 Epoxy Composites	146
6-2B.	Specific Heat of E-Glass Fiber DEN-438 Epoxy Composites	147
6-2C.	Specific Heat of E-Glass Fiber Narmco Epoxy Composites	148
6-2D.	Specific Heat of YM-31-A Glass Fiber DER-332 Epoxy Composites	149
6-3A.	Longitudinal Thermal Linear Expansion of YM-31-A Glass Fiber DER-332 Epoxy Composites	160
6-3B.	Longitudinal Thermal Linear Expansion of E-Glass DER-332 Epoxy Composites	161
6-3C.	Longitudinal Thermal Linear Expansion of E-Glass Fiber DEN-438 Epoxy Composites	162
6-3D.	Transverse Thermal Linear Expansion of YM-31-A Glass Fiber DER-332 Epoxy Composites	163
6-3E.	Transverse Thermal Linear Expansion of E-Glass Fiber DER-332 Epoxy Composites	164
6-3F.	Transverse Thermal Linear Expansion of E-Glass Fiber DEN-438 Epoxy Composites	165
7- 1.	Thermal Conductivity of Graphite Fiber Epoxy Composites	181
7- 2.	Specific Heat of Graphite Fiber Epoxy Composites	187
7-3A.	Longitudinal Thermal Linear Expansion of High Modulus Graphite Fiber Epoxy Composites	195
7-3B.	Transverse Thermal Linear Expansion of High Modulus Graphite Fiber Epoxy Composites	196
7-3C.	Thermal Linear Expansion of Pseudo Isotropic Graphite Fiber Epoxy Composites	197
7-3D.	Longitudinal Thermal Linear Expansion of High Strength Graphite Fiber Epoxy Composites	198
7-3E.	Transverse Thermal Linear Expansion of High Strength Graphite Fiber Epoxy Composites	199

1. INTRODUCTION

This work presents both the available experimental data that were exhaustively searched and comprehensively compiled for five thermophysical properties of seven selected aerospace materials and the recommended values resulting from critical evaluation, analysis, and synthesis of the available data and information. The five thermophysical properties are: (1) thermal conductivity, (2) specific heat, (3) heat of fusion, (4) thermal linear expansion, and (5) thermal diffusivity. The seven selected materials are: (1) aluminum alloy 2024, (2) AISI 304 stainless steel, (3) Pyroceram (Corning 9606), (4) silicon nitride (Si_3N_4), (5) boron fiber epoxy composite, (6) glass fiber epoxy composite, and (7) graphite fiber epoxy composite.

In order to assist the reader to properly interpret and fully utilize the data and information presented in this work, Section 2 provides the general background information on the behavior of each of the thermophysical properties covered, the procedures used for the data evaluation and the generation of recommended values, and on the format and detail of the data presentation. The experimental data and the recommended values for the five properties of the seven materials are presented in Section 3 in both tabular and graphical forms, together with a discussion text for each property of each material, in which the individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, and the uncertainty of the recommended values is stated. Since the information on some of the selected materials is not generally known, a concise description of each of the materials is given at the beginning of each of the subsections in Section 3. The complete bibliographic citations for the 156 references are given in Section 4.

2. GENERAL BACKGROUND

The purpose of this section is to provide general background information on the thermophysical properties covered in this work, the procedures for the data evaluation and the generation of recommended values, and on the format of presentation of data. It is hoped that this information will assist the reader to properly interpret and fully utilize the data and information presented in this work and also enhances the usefulness of the data themselves.

2.1. Thermophysical Properties

In this work five thermophysical properties are covered: thermal conductivity, specific heat, heat of fusion, thermal linear expansion, and thermal diffusivity. These are briefly discussed below.

Thermal Conductivity

In metals and alloys the principal carriers of heat are electrons and lattice vibrational waves. In a pure metal the heat conduction by electrons is predominant at all temperatures and the contribution to heat conduction by lattice waves is comparatively very small.

In an alloy, especially at low temperatures, however, the contribution by lattice waves is often comparable to and sometimes even greater than that by electrons. Consequently, in estimating or analyzing the thermal conductivity data for an alloy, the consideration of both electronic and lattice components of the thermal conductivity is necessary. At very low temperatures the electronic thermal resistivity arises from the scattering of electrons by solute atoms, and at higher temperatures the scattering of electrons by lattice waves becomes significant.

In nonmetallic solids the conduction of heat is mainly by lattice vibrational waves. The quanta of vibrational energy are called phonons, and the thermal conductivity of non-metallic solids is determined both by the specific heat and the mean free path of the phonons. The mean free path is limited by the various phonon scattering processes, which give rise to thermal resistance. At temperatures close to absolute zero the phonons are scattered by the crystal boundaries, and the thermal conductivity of a non-metallic crystal varies as T^3 (the temperature dependence of the lattice specific heat) and is size dependent. As the temperature is increased, other scattering mechanisms become effective: scattering of phonons by static imperfections (impurities, isotopes,

and all kinds of lattice defects) and scattering of phonons by other phonons (Umklapp processes). The last mentioned process increases rapidly with temperature, until the mean free path decreases more rapidly with temperature than the specific heat increases. At this point, still at very low temperature, the thermal conductivity passes through a maximum and then decreases, in some perfect crystals exponentially. Around the Debye temperature and above, the phonon-phonon (Umklapp) scattering is predominant and the thermal conductivity should vary as T^{-1} . In some cases the crystals are at least partially transparent to infrared radiation, and there is an additional radiative component of thermal conductivity, which increases rapidly with temperature at high temperatures. In other cases such as in mixed crystals and in disordered crystals, the thermal conductivity varies slower than T^{-1} due to the combined resistance of Umklapp processes which varies as T and of phonon-defect scattering processes which at high temperatures is more or less independent of temperature. In the extreme cases of highly disordered solids such as in amorphous or vitreous materials, the disorder determines the phonon mean free path which consequently becomes constant at high temperatures, and the thermal conductivity increases with temperature, being roughly proportional to the specific heat of the material.

The thermal conductivity of a composite material is affected by many factors such as the thermal conductivities of the components, the composition and structure of the composite, the manufacturing process, the heat treatment, and the direction of heat flow. Thus it is a highly complicated quantity and can only be roughly estimated by semiempirical relations.

Specific Heat

In nonmetallic solids the specific heat is solely due to lattice vibrations, and the lattice specific heat is thus the total specific heat. In metals and alloys, however, in addition to the lattice specific heat there is another component due to the contribution from the electrons, though the electronic component is relatively small except at low temperatures.

The lattice specific heat of a solid at moderate and high temperatures (above the Debye temperature) is nearly constant, increasing only slightly with temperature. The Dulong and Petit law states that the specific heat of all solid elements at room temperature is nearly the same and equals about $6.4 \text{ cal mol}^{-1} \text{ K}^{-1}$. This law is closer to the truth for heavy elements with atomic weights greater than 38. For chemical compounds the Kopp-Neumann law states that the molar specific heat of a compound is equal to the sum of the atomic specific heats of its constituent elements. The Kopp-Neumann law can also be applied approximately to alloys.

At low temperatures the lattice specific heat decreases sharply with decreasing temperature, tending toward zero and varying as T^3 as the temperature approaches the absolute zero. This fact has been explained by the theory of Debye.

The electronic specific heat of a metal or alloy varies linearly with temperature. At high temperatures it is small compared with the lattice specific heat. At low temperatures, however, it becomes comparable with the lattice component, and can even exceed it at the lowest temperatures, at which, though, both components are rather small.

The specific heat of a solid which exhibits any kind of transitions such as phase, magnetic, order-disorder, etc. is anomalous and a peak occurs in the specific heat versus temperature curve in the vicinity of the transition. This is because an extra amount of heat must be supplied to the solid to bring about such a transition.

Heat of Fusion

The heat of fusion of a substance is the amount of heat required to change a given mass of a substance from the solid to the liquid state without change in temperature. For solutions of two or more components, the melting process normally occurs over a range of temperatures, and a distinction is made between the melting point, the point at which the first trace of liquid appears, and the freezing point, the highest temperature at which the last trace of solid disappears. The heat of fusion of pure elements or congruently melting compounds can be measured directly or can be rigorously calculated from the slopes of the liquidus and solidus.

The heat of fusion studies for the materials covered in this work are nonexistent. This may be either due to the melting process occurring over a wide range of temperature as in case of alloys or due to the tendency of the material to dissociate (Si_3N_4) and to soften (Pyroceram and Composites) at elevated temperature. In many cases the heat of fusion of a material may be calculated from the heats of fusion of the components, if the latter are available.

Thermal Linear Expansion

Most materials increase in size upon heating. The total thermal linear expansion from absolute zero to the melting point is about 2 to 3% for most solids. Thermal expansion arises from the fact that the thermal vibrations of the atoms or molecules about their equilibrium positions in the crystalline lattice are anharmonic, that is, the forces acting between pairs of atoms or molecules are not proportional to their relative displacements. If the thermal vibrations were perfectly harmonic, as is generally assumed in the theory of the specific heat, there would be no thermal expansion, by either classical or quantum mechanical reasoning.

In this work the recommended values are given for both the percent thermal linear expansion, $\Delta L/L_0(\%)$, and the instantaneous coefficient of thermal linear expansion, α . These are defined as:

$$\frac{\Delta L}{L_0} (\%) = \frac{L_T - L_0}{L_0} \times 100$$

and

$$\alpha = \frac{d}{dT} \left(\frac{\Delta L}{L_0} \right) = \frac{1}{L_0} \frac{dL}{dT}$$

where L_T and L_0 are lengths of the material (or lattice parameters) at temperature T and at 293 K, respectively.

Grüneison found that the instantaneous coefficient of thermal expansion is approximately linearly proportional to the constant-volume specific heat. Thus at absolute zero temperature, the expansion coefficient is zero, as does the specific heat. As the temperature is increased from absolute zero, the expansion coefficient increases rather rapidly from zero and finally levels off to a nearly constant value.

The thermal expansion of a solid which exhibits a phase transition has a discontinuity in the vicinity of the transition, at which the expansion coefficient is momentarily infinite.

Thermal Diffusivity

Thermal diffusivity is a ratio of the thermal conductivity to the specific heat per unit volume. When heat flows through a material under nonsteady-state conditions, one may visualize the thermal diffusivity as an indication of the ratio of the amount of heat flowing out of a volume of the material to the amount of heat retained within the volume.

Since the range of variation of the thermal conductivity with temperature is small relative to that of the specific heat, the behavior of the thermal diffusivity is influenced more markedly by the behavior of the specific heat, and the thermal diffusivity versus temperature curve looks somewhat like an inversed specific heat curve. In other words, the thermal diffusivity of a material generally is very high at the lowest temperatures; as the temperature is increased the thermal diffusivity decreases rapidly and finally levels off at higher temperatures.

Thermal diffusivity of a material can be measured directly and can also be calculated from the values of thermal conductivity, specific heat, and density.

2.2. Data Evaluation and Generation of Recommended Values

Due to the difficulties in accurate measurement of thermophysical properties of solids and in adequate characterization of test specimens, the available experimental data from the world literature are in many cases widely divergent and subject to large uncertainty. It is, therefore, very important to critically evaluate and analyze the available data and to generate recommended values. The procedure involves critical evaluation of the validity and reliability of the data and related information, resolution and reconciliation of disagreements in conflicting data, correlation of data in terms of various controlling parameters, curve fitting with theoretical or empirical equations, comparison of results with theoretical predictions or with results derived from theoretical relationships or from generalized empirical correlations, etc. Besides critical evaluation and analysis of existing data, theoretical methods and semiempirical techniques are employed to fill data gaps and to synthesize fragmentary data so that the resulting recommended values are internally consistent and cover as wide a range of temperature as possible.

Considering the thermal conductivity, for example, in the critical evaluation of the validity and reliability of a particular set of thermal conductivity data, the temperature dependence of the data was examined and any unusual dependence or anomaly carefully investigated, the experimental technique was reviewed to see whether the actual boundary conditions in the measurement agreed with those assumed in the theory and whether all the stray heat flows and losses were prevented or minimized and accounted for, the reduction of data was examined to see whether all the necessary corrections had been appropriately applied, and the estimation of uncertainties was checked to ensure that all the possible sources of errors had been considered.

Experimental data could probably be judged to be reliable only if all sources of systematic error had been eliminated or minimized and accounted for. Major sources of systematic error include unsuitable experimental method, poor experimental technique, poor instrumentation and poor sensitivity of measuring devices, sensors, or circuits, specimen and/or thermocouple contamination, unaccounted for stray heat flows, incorrect form factor, and perhaps most important, the mismatch between actual experimental boundary conditions and those assumed in the analytical model used to derive the value of thermal conductivity. These and other possible sources of errors are carefully considered in critical evaluation of experimental data. The uncertainty of a set of data depends, however, not only on the estimated error or inaccuracy of the data but also on the inadequacy of characterization of the material for which the data are reported.

In many cases, however, research papers do not contain adequate information for a data evaluator to perform a truly critical evaluation. In these cases, some other considerations might have to be used for data evaluation. For instance, if several authors' data agree with one another and, more importantly, these were obtained by using different experimental methods, these data are likely to be reliable. However, if the data were observed by using the same experimental method, even though they all agree, the reliability of the data is still subject to questioning, because they may all suffer from a common, but unknown source of error. Secondly, if the same apparatus has been used for measurements of other materials and the results are reliable, and if the result of measurement on the new material is in the same range, the result for the new material is likely to be reliable.

If the information given by the author is entirely inadequate to make any value judgment, the data assessment becomes subjective. At times judgments might be based upon factors and considerations such as the purpose and motivation for the measurement, general knowledge of the experimenter, his past performance, the reputation of his laboratory, etc.

In the process of critical evaluation of experimental data outlined above, the majority of unreliable and erroneous data were eliminated. The remaining data were then subjected to further analysis, correlation, and synthesis. If a number of data sets are available for a well-characterized material, correlation of the data in terms of the affecting parameters could be made. Applying the principle of corresponding states, reduced property values might be correlated with reduced temperature and other reduced parameters. Furthermore, by using theoretical relationships, several properties of a given material could be cross-correlated to check for internal consistency of the data or for data estimation.

Depending upon the level of confidence the data analyst has placed on the values and upon the degree of adequacy of characterization of the material for which the values are generated, the reported values are designated as "recommended values" or "provisional values". In this work all the values generated are properly designated, and the accuracy or uncertainty of the values is clearly stated.

2.3. Presentation of Data

In each of the subsections of Section 3, the property data and information are presented in the following order: (1) discussion text, (2) table of recommended values, (3) figure presenting recommended curve(s) and experimental data, (4) table giving experimental information, and (5) table of experimental data.

In the discussion text, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties of the recommended values are stated.

The values given in the table are designated either as recommended or provisional values depending upon the level of confidence placed on the values and, hence, upon the uncertainty assigned. The ranges of uncertainties of recommended and provisional values for specific heat, percent thermal linear expansion, and density are $\leq \pm 5\%$ and $> \pm 5\%$, respectively. Those for thermal conductivity, thermal diffusivity, and instantaneous coefficient of thermal linear expansion are $< \pm 15\%$ and $\geq \pm 15\%$, respectively. In the tables the third significant figure is generally given for the property values; this, however, is only for internal comparison and for tabular smoothness and should not be considered indicative of the degree of accuracy or uncertainty. The uncertainty of the values is always explicitly stated.

In the figure presenting recommended curve(s) and experimental data, the curve numbers correspond to those listed in the accompanying table on measurement information and table of experimental data. When several sets of data are too close together to be distinguishable, some of the data sets, though listed in the tables, are omitted from the figure for the sake of clarity.

The table containing measurement information gives for each set of experimental data the following information: the curve number, the publication reference number, author's name, year of publication, experimental method used for the measurement, temperature range covered by the data, name and specimen designation, composition, specification and characterization of the specimen and information on measurement condition, which are contained in the original paper. In these tables the code designations used for the experimental methods for property measurements are listed below.

For thermal conductivity measurements:

C	Comparative method
E	Direct electrical heating method
L	Longitudinal heat flow method
P	Periodic or transient heat flow method
R	Radial heat flow method

For specific heat measurements:

A	Adiabatic method
DSC	Differential scanning calorimeter
DTA	Differential thermal analysis
I	Ice calorimeter

For thermal linear expansion measurements:

I	Interferometer method
L	Dilatometer method
X	X-ray diffraction method
V	Variable-induction transformer

In the table of experimental data, all the available data shown or not shown in the figure are tabulated.

3. THERMOPHYSICAL PROPERTIES OF SELECTED MATERIALS

3.1. Aluminum Alloy 2024

Aluminum Alloy 2024, formerly known as Aluminum Alloy 24S, is a wrought alloy with copper as the principal alloying element. Its nominal composition [1] is (by weight) 4.5% Cu, 1.5% Mg, 0.6% Mn, and balance Al. It is perhaps the best known and most widely used aircraft alloy.

Some physical [2] and mechanical properties [3] of this alloy are as follows: solidus temperature, 775 K; liquidus temperature, 911 K; specific gravity, 2.77; tensile (ultimate) strength, 19.0-51.0 kg/mm²; Brinell hardness number (500 kg load, 10 mm ball), 47-130. The mechanical properties vary over a wide range due to differences in applied heat treatments.

This alloy requires solution heat-treatment to obtain optimum properties. In the well heat-treated condition, the mechanical properties of this alloy are similar to, and sometimes exceed, those of mild steel. A particular heat treatment is specified by a letter "T" after the 2024 designation, followed by one of the numerals from 1 to 10, such as Aluminum Alloy 2024-T4. Briefly, these heat treatments are as follows [3]:

- T1 - cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.
- T2 - annealed (cast products only).
- T3 - solution heat-treated and then cold worked.
- T4 - solution heat-treated and naturally aged to a substantially stable condition.
- T5 - cooled from an elevated temperature shaping process and then artificially aged.
- T6 - solution heat-treated and then artificially aged.
- T7 - solution heat-treated and then stabilized.
- T8 - solution heat-treated, cold worked, and then artificially aged.
- T9 - solution heat-treated, artificially aged, and then cold worked.
- T10 - cooled from an elevated temperature shaping process, artificially aged, and then cold worked.

Each of these treatments [1] has a unique effect on the mechanical properties of the alloy. The designations, however, do not define the time and temperature of the heat treatments, and the details of the practice may be varied as desired or convenient if the end result as expressed by specified mechanical properties is unchanged. Should a variation of a basic operation be applied to the alloy, resulting in different characteristics, other digits are added to the basic designation, such as Aluminum Alloy 2024-T81,

Aluminum Alloy 2024-T851, etc. The second and third numerals in the heat treatment designation are arbitrary, generally having no logical significance. In the earlier designations the heat treatments were not catalogued as above. An alloy might be designated as Aluminum Alloy 24S-T, where the T only means that the alloy was tempered to a stable condition.

This alloy does not have as good corrosion resistance properties as most other aluminum alloys and under certain conditions may be subjected to intergranular corrosion. Therefore, it is widely used in the clad, anodized, or alodined states. In the clad [3] state the alloy is protected from corrosion by a thin surface of a pure metal or alloy with a higher solution potential. The term alclad is used when the cladding material is pure aluminum. The anodizing [1] process involves forming a conversion coating on the metal surface by anodic oxidation. Alodining is also a process of forming a conversion coating, with the coating being some other type of material such as a phosphate or chromate. These processes greatly increase the resistance of Aluminum Alloy 2024 to corrosion.

a. Thermal Conductivity

There are eighteen sets of data available, all measured below 730 K, and four of these reach down to low temperatures. Most of the measurements are for specimens designated either as 2024-T4 or 2024-T351. The available experimental data are tabulated in Table 1-3 and shown partially in Figure 1-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 1-2. One data set (curve 18) for a Duraluminum specimen is also included in the compilation to assist in the data analysis at low temperatures.

The recommended values tabulated in Table 1-1 and shown in Figure 1-1 are for both as-received and annealed alloy samples. Those for as-received alloy are for an as-received alloy 2024-T4 with a residual electrical resistivity of $3.2 \mu\Omega$ cm. The recommended values at cryogenic temperatures are based on the data of Powell et al. [4] (curve 4). At temperatures between 120 and 600 K, the recommended values are based on the data of Lucks et al. [6] (curve 1). Above 600 K, the data of Lucks et al. [6] (curve 2) and of Evans [7] (curves 13 and 14) decrease sharply as the temperature increases. These authors employed the comparative technique using Armco iron or lead as standards in their thermal conductivity measurements. Since Armco iron has a strong but negative temperature dependence at high temperatures and lead melts at 600.652 K, the results of these authors above 600 K are questionable. Hence, the recommended

values above 600 K do not follow the experimental data, but are extended to the solidus point according to the general trend of the temperature dependence established for the thermal conductivity of Al + Cu and Al + Mg binary alloys [8]. In the molten state, the recommended values were calculated from the equation:

$$\frac{1}{k} = \sum_i \frac{x_i}{k_i}$$

where x_i is the atomic fraction, and k_i is the thermal conductivity of the i th constituent element of the alloy. The error of the calculated values should be small since x_{Al} is much larger than the other x_i 's.

If the alloy is heated at an elevated temperature (above 400 K) for a long period of time, the thermal conductivity will increase remarkably. The recommended values for the thermal conductivity of such annealed alloy having residual electrical resistivity of about $0.70 \mu\Omega \text{ cm}$ are also presented. These values depart from those for the as-received alloy below about 600 K and follow the data of Lucks et al. (curve 2) to 150 K. Above 600 K the values follow the general trend of the temperature dependence of thermal conductivity established for Al + Cu and Al + Mg binary alloys [8].

The uncertainty of the recommended values is believed to be within $\pm 10\%$ at temperatures below 200 K, $\pm 5\%$ from 200 to 600 K, $\pm 8\%$ from 600 K to the solidus point, and within $\pm 10\%$ and -16% in the liquid region.

**TABLE 1-1. RECOMMENDED THERMAL CONDUCTIVITY OF
ALUMINUM ALLOY 2024**

[Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹]

T	k	
	As received	Annealed
4	0.0316	
7	0.0566	
10	0.0822	
15	0.126	
20	0.169	
25	0.210	
30	0.251	
40	0.326	
50	0.394	
60	0.456	
70	0.510	
80	0.560	
90	0.608	
100	0.650	
150	0.842	1.55
200	1.01	1.63
250	1.14	1.70
273.15	1.19	1.73
293	1.23	1.76
300	1.24	1.77
350	1.33	1.82
400	1.41	1.86
450	1.60	1.88
500	1.77	1.89
550	1.83	1.88
600	1.85	1.86
650	1.83	1.83
700	1.80	1.80
750	1.76	1.76
775 [†]	1.73	1.73
911 [†]	0.872	0.872
950	0.888	0.888
1000	0.905	0.905
1100	0.937	0.937

[†] Melting Range 775-911 K.

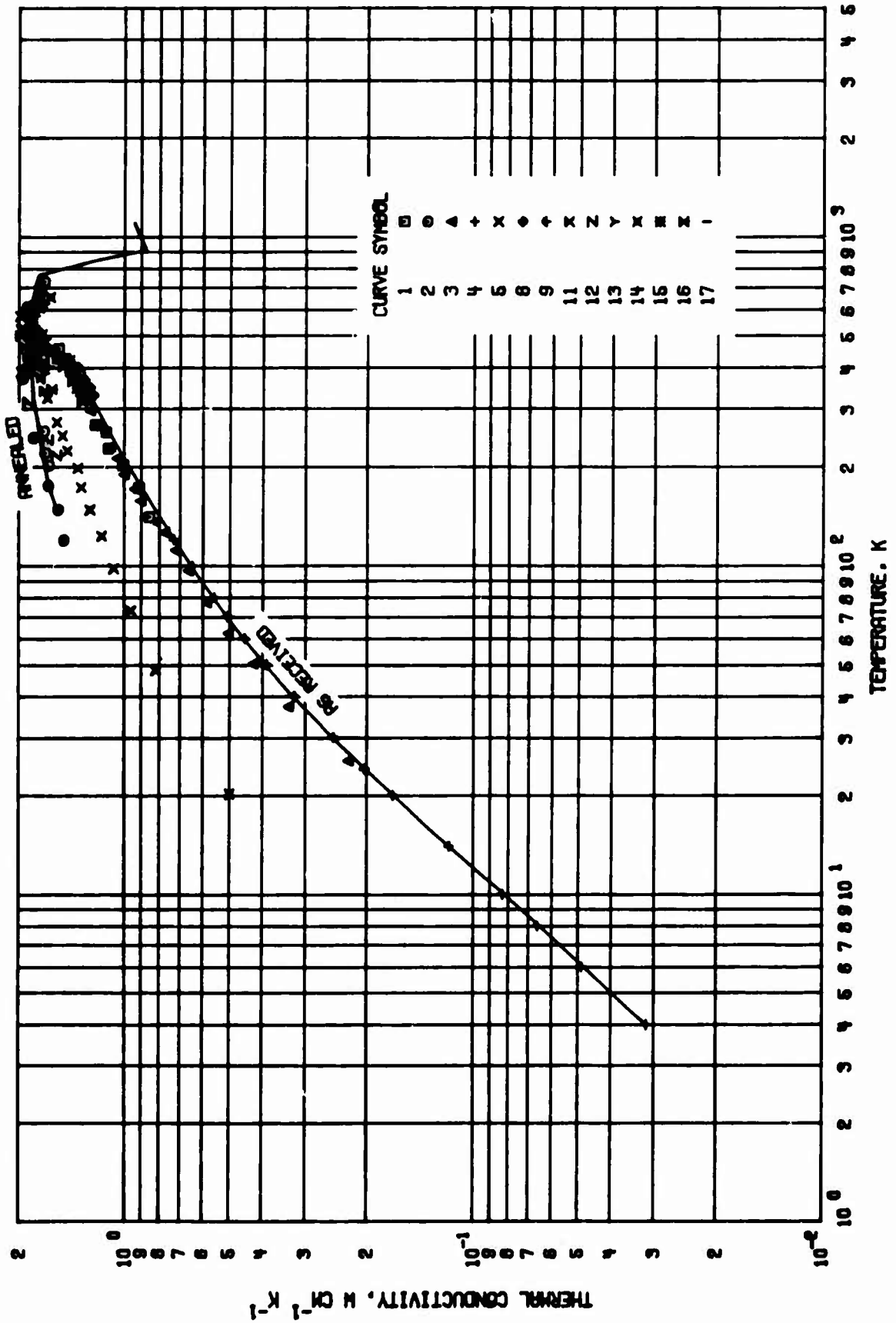


FIGURE 1-1. THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 .

TABLE 1-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent)					Composition (continued), Specifications, and Remarks	
						Al	Cu	Fe	Mg	Mn		Ni
1 6	Lucks, C. F., Thompson, H. B., Smith, A. R., Curry, F. P., Deem, H. W., and Bing, G. F.	1951	C	140-552	24S-T4		4.5		1.5	0.6		As received; Armco iron used as comparative material.
2 6	Lucks, C. F., et al.	1951	C	119-731			4.5		1.5	0.6		The above specimen heated to 300 C.
3 9	Powers, R. W., Ziegler, J. B., and Johnston, H. L.	1951	L	26-296	24S		4.49	0.34	1.47	0.66		0.13 Si, 0.02 Ti, 0.01 Cr, and 0.01 Zn; as reported by Alcoa; reported error <2.0%.
4 4	Powell, R. L., Hall, W. J., and Roder, H. M.	1960	L	4.0-120	2024-T4		4.58	0.1	1.7	0.1		0.1 each Ga, Si, V, Zn, 0.05 Cr, 0.01 each Sn, Ti, and 0.001 each Ca, Ag, Zr; grain size 0.08 mm by 0.052 mm (longitudinal) and 0.048 mm (transverse); solution heat-treated; electrical resistivity 3.2, 3.2, 3.3, 3.5, 4.2, 5.5, and 6.1 $\mu\Omega$ cm at 4, 10, 40, 60, 100, 200, and 300 K, respectively; smoothed values reported.
5 10	Rhodes, B. L., Moeller, C. E., and Sauer, H. J.	1965	L	20-573	Al-2014-T6		92.61	4.57	0.44	0.45	0.93	0.88 Si, 0.06 Zr, 0.04 Ti, and 0.02 Cr.
6* 11	Garth, R. C. and Saller, V. L.	1949	L	298.2	24S-T4							3.500 in. diameter by 4.000 in. high.
7* 11	Garth, R. C. and Saller, V. L.	1949	L	298.2	24S-O							The above specimen annealed.
8 12, 13	Williams, D. R. and Blum, H. A.	1966	L	329-419	Al 2024-T351		4.5		1.5	0.6		Nominal composition; specimen ~0.4 cm in diameter and ~0.37 meters long; thermal conductivity values averaged over 2 runs measured by W & R method.
9 12, 13	Williams, D. R. and Blum, H. A.	1966	L	329-417	Al 2024-T351		4.5		1.5	0.6		Similar to the above specimen except measured by a "no-loss" method.
10* 12, 13	Williams, D. R. and Blum, H. A.	1966	C	329-417	Al 2024-T351		4.5		1.5	0.6		Similar to the above specimen except measured by comparative method and Armco iron used as comparative material.
11 14	Smuda, P. A., Fletcher, L. S., and Gyorgog, D. A.	1967	L	314-450			4.5		1.5	0.6		Nominal composition; two cylinders 1.625 in. diameter by 4.50 in. long joined by a central heater; as received.
12 14	Smuda, P. A., et al.	1967	L	215-523			4.5		1.5	0.6		The above specimen annealed.
13 7	Evans, J. E., Jr.	1951	C	384-634	Al alloy 24S		4.5		1.5	0.6		Nominal composition; NBS M. P. standard lead used as comparative material.
14 7	Evans, J. E., Jr.	1951	C	382-655	Al alloy 24S		4.5		1.5	0.6		The above specimen; second run.
15 15	Clausing, A. M.	1963	L	338-427	2024-T4		3.8-4.9	0.50	1.2-1.8	0.30-0.9		0.50 Si, 0.25 Zn, 0.10 Cr, and 0.15 others (nominal composition); cylindrical specimen.

* Not shown in figure.

TABLE 1-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 (continued)

Cur. Ref. No. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Al	Cu	Composition (weight percent)			Composition (continued), Specifications, and Remarks
16 15	Clausing, A. M.	1963	L	344, 419	2024 T4		3.8- 4.9	0.50	1.2- 1.8	0.30- 0.9	The above specimen annealed at 467 K. 0.50 Si, 0.25 Zn, 0.10 Cr, and 0.15 others (nominal composition); 1.375 in. diameter by 2.5 in. long; machined. 7.5 x 6.5 mm tube; reported error < 5.0%.
17 16	Abbott, R. E.	1967	L	311, 319	2024 T4		3.8- 4.9	0.50	1.2- 1.8	0.30- 0.9	
18* 5	Zavaritskii, N. V., and Zeldovich, A. G.	1956	L	3.3-81	Duraluminum D16		4.4		1.5	0.6	

* Not shown in figure.

TABLE 1-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF ALUMINUM ALLOY 2024 (continued)

T	k
<u>CURVE 15</u>	
338	1.333
343	1.263
344	1.296
346	1.362
349	1.314
421	1.424
421	1.450
421	1.473
427	1.532
427	1.565
<u>CURVE 16</u>	
344	1.615
419	1.705
<u>CURVE 17</u>	
311	1.25
319	1.27
<u>CURVE 18*</u>	
3.28	0.0490
3.90	0.0619
4.22	0.0703
5.20	0.0879
5.95	0.0971
6.22	0.116
8.0	0.137
10.4	0.172
12.4	0.209
16.2	0.259
19.4	0.293
22.0	0.305
24.5	0.377
30.5	0.464
39.0	0.586
50.5	0.749
63.5	0.837
81.0	0.879

* Not shown in figure.

b. Specific Heat

There are 20 sets of experimental data available for the specific heat of Aluminum Alloy 2024. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 1-5. The experimental data are tabulated in Table 1-6 and partially shown in Figure 1-2.

Most of the measurements were carried out within the temperature range 75-700 K. The recommended values shown in Figure 1-2 and tabulated in Table 1-4 agree well with most of the measurements reported in the experimental data table with the exception of the data of Makarounis and Jenkins [17] (curve 3) which are about 10% higher than the recommended values. The data of Suzuki [18] (curve 11) show a sudden increase above 600 K. Suzuki [18] (curves 13-20) also found anomalies near 473 and 550 K for the specimens aged at various temperatures and times. Specific heat values for this alloy calculated using the Kopp-Neumann mixing rule agree well at temperatures below 500 K and about 4-10% lower at higher temperatures. The specific heat of pure aluminum is about 5-15% lower than that of this alloy.

The melting range for this alloy is 775-911 K. No experimental data for the specific heat of this alloy in the liquid state were located in the literature. Considering the agreement of the specific heat values calculated using the Kopp-Neumann mixing rule with the experimental data for the solid alloy, this mixing rule should well be applied to the specific heat values for the molten alloy. The specific heat values for the molten alloy are thus calculated. In the calculations the specific heat values for the constituent elements are taken from Hultgren et al. [19]. The values for the molten pure aluminum are about 4% lower than the tabulated values for the molten alloy.

The uncertainty of the recommended values for the solid alloy is believed to be within $\pm 5\%$. The values for the molten alloy are provisional and their uncertainty is within $\pm 10\%$.

TABLE 1-4. RECOMMENDED SPECIFIC HEAT OF
ALUMINUM ALLOY 2024

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p
100	0.113
150	0.158
200	0.188
250	0.200
273.15	0.205
293	0.208
300	0.209
350	0.216
400	0.221
450	0.226
500	0.233
550	0.241
600	0.249
650	0.258
700	0.269
750	0.280
775 [†]	0.286
911 [†]	0.300 [‡]
1000	0.300 [‡]
1100	0.300 [‡]
1200	0.300 [‡]

[†] Melting region 775-911 K.

[‡] Provisional value.

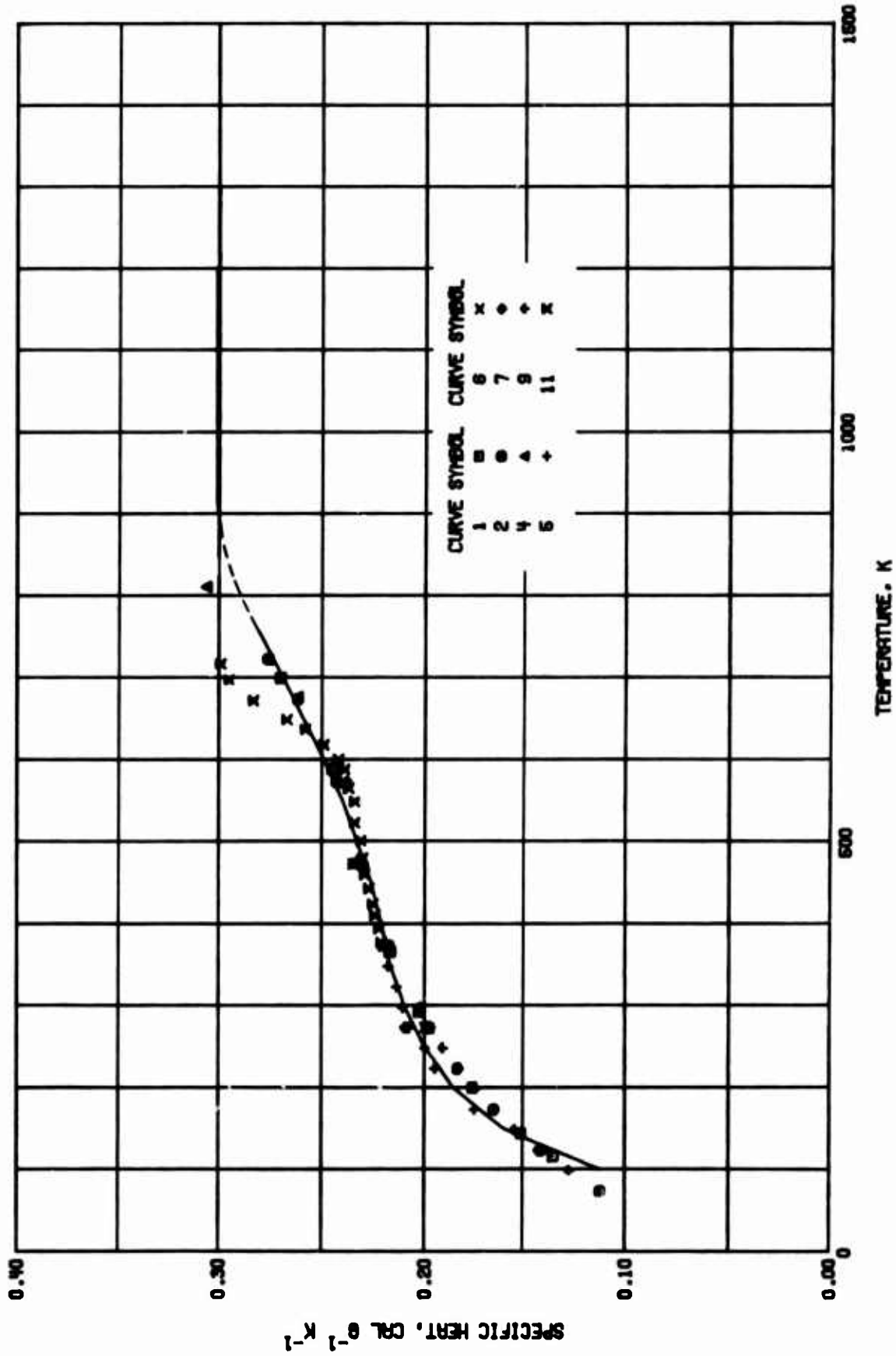


FIGURE 1-2. SPECIFIC HEAT OF ALUMINUM ALLOY 2024 .

TABLE 1-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 20	Lucks, C.F. and Deem, H.W.	1958		116-700		Specimen with nominal composition from Alcoa; measurements using ice calorimeter.
2 21	Lucks, C.F., Matolich, J., and Vanvelsor, J.A.	1954		73-723		Specimen with nominal composition.
3* 17	Makarov, O. and Jenkins, R.J.	1962		97-468		Specimen with nominal composition; Hanovia liquid platinum was applied on both surfaces of the specimen for good conduction; front surface was painted for opaqueness.
4 22	Schafly, J.M.	1964		272-811		No details given.
5 23	Makarounis, O.	1966		173-373		Values calculated from spectral properties of its surface and irradiance energy.
6 24	Dietz, J.L.	1956		273-573		Data of Battelle Memorial Institute.
7 24	Dietz, J.L.	1956		273-573		Data of Battelle Memorial Institute.
8* 25	Zoller, P. and Dillinger, J.R.	1969		1.6-4		Specimen from Alcoa, a slight up-turn in C_p/T values below 2 K observed; data is represented by $C = \gamma T + BT^3$ ($\gamma = 1.396 \text{ m J mole K}^{-1}$, $B = 0.0287 \text{ m J mole}^{-1} \text{ K}^{-4}$), molecular weight = 27.780.
9 26	Makarounis, O.	1967		98-298		Values calculated from spectral properties of its surface and irradiance energy.
10* 26	Makarounis, O.	1967		90-298		Data of Battelle Memorial Institute (after 6145, part III).
11 18	Suzuki, T.	1949				4.31 Cu, 0.29 Si, 0.14 Fe, and Al balance; specimen was melted in high frequency induction furnace, hot worked and recrystallized by annealing in vacuum at 773 K for several hr.
12* 18	Suzuki, T.	1949		373-504		Similar to the above specimen except specimen quenched from 793 K in water at room temperature.
13* 18	Suzuki, T.	1949		373-606		Similar to the above specimen except the specimen aged at 293 K for 30 days.
14* 18	Suzuki, T.	1949		373-728		Similar to the above specimen except the specimen aged at 383 K for 23.5 hr.
15* 18	Suzuki, T.	1949		373-697		Similar to the above specimen except the specimen quenched from 793 K and aged at 423 K for 1 hr.
16* 18	Suzuki, T.	1949		373-607		Similar to the above specimen except the specimen aged for 1.5 hr.
17* 18	Suzuki, T.	1949		373-601		Similar to the above specimen except the specimen aged for 2 hr.
18* 18	Suzuki, T.	1949		373-609		Similar to the above specimen except the specimen aged for 5 hr.
19* 18	Suzuki, T.	1949		379-603		Similar to the above specimen except the specimen aged for 10 hr.
20* 18	Suzuki, T.	1949		378-692		Similar to the above specimen except the specimen aged for 22.5 hr.

* Not shown in figure.

TABLE 1-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024

[Temperature, T, K; Specific Heat, C_p , cal · K ⁻¹ g ⁻¹]			
T	C_p	T	C_p
CURVE 1			
116	0.135	217	0.206
144	0.151	215	0.211
200	0.176	217	0.213
293	0.203	221	0.216
366	0.217	281	0.220
477	0.231	295	0.218
589	0.245	299	0.222
700	0.270	315	0.224
CURVE 2			
73	0.112	331	0.226
123	0.141	334	0.229
173	0.165	343	0.229
223	0.184	349	0.234
273	0.198	375	0.233
373	0.218	393	0.236
473	0.231	399	0.235
573	0.243	411	0.238
673	0.262	435	0.238
723	0.276	439	0.234
CURVE 3*			
97	0.103	440	0.237
103	0.106	443	0.241
105	0.113	445	0.235
111	0.124	455	0.242
115	0.128	466	0.242
123	0.140	468	0.236
129	0.145	CURVE 4	
133	0.148	272	0.198
135	0.157	372	0.218
139	0.160	466	0.230
163	0.169	572	0.243
163	0.172	677	0.262
165	0.175	722	0.276
169	0.178	811	0.306
169	0.198	CURVE 5	
177	0.179	173	0.175
185	0.186	223	0.195
190	0.187	248	0.200
214	0.193	273	0.208
215	0.202	298	0.211
217	0.198	323	0.214
217	0.200	348	0.218
CURVE 6			
217	0.200	373	0.220
CURVE 7			
273	0.210	377	0.221
373	0.220	394	0.222
473	0.235	410	0.224
573	0.238	424	0.225
CURVE 8*			
1.6	0.155	443	0.227
2	0.200	460	0.229
3	0.328	480	0.230
4	0.491	501	0.231
CURVE 9			
98	0.127	523	0.234
123	0.142	549	0.234
148	0.154	565	0.237
173	0.165	588	0.239
198	0.174	600	0.242
223	0.183	618	0.249
248	0.191	637	0.258
273	0.197	649	0.267
298	0.202	672	0.263
CURVE 10*			
90	0.097	697	0.295
93	0.103	717	0.299
98	0.110	CURVE 11	
103	0.116	273	0.206
108	0.122	298	0.210
113	0.127	CURVE 12*	
118	0.134	373	0.220
123	0.136	383	0.221
133	0.145	399	0.230
148	0.158	407	0.230
173	0.172	420	0.227
198	0.186	431	0.231
223	0.196	441	0.233
248	0.201	451	0.232
CURVE 13*			
373	0.227	460	0.229
379	0.229	471	0.229
392	0.229	483	0.229
402	0.234	494	0.227
CURVE 14*			
373	0.224	504	0.224
389	0.228	CURVE 15*	
400	0.230	416	0.238
413	0.238	431	0.238
421	0.244	448	0.232
427	0.249	468	0.230
436	0.260	482	0.230
442	0.265	493	0.230
452	0.270	507	0.223
456	0.270	518	0.209
461	0.262	523	0.190
469	0.252	530	0.174
476	0.244	535	0.160
487	0.241	543	0.144
496	0.235	548	0.142
508	0.227	554	0.151
518	0.217	566	0.170
526	0.203	576	0.188
538	0.180	594	0.203
567	0.192	590	0.219
572	0.207	599	0.248
582	0.225	609	0.237
589	0.235	623	0.263
599	0.247	643	0.272
611	0.262	660	0.273
CURVE 15*			
373	0.219	680	0.271
383	0.224	697	0.265
393	0.229	CURVE 16*	
404	0.231	416	0.238
413	0.229	431	0.238
425	0.228	448	0.232
429	0.240	468	0.230
438	0.233	482	0.230
448	0.236	493	0.230
458	0.232	507	0.223
468	0.230	518	0.209
482	0.230	523	0.190
493	0.230	530	0.174
507	0.223	535	0.160
518	0.209	543	0.144
523	0.190	548	0.142
530	0.174	554	0.151
535	0.160	566	0.170
543	0.144	576	0.188
548	0.142	594	0.203
554	0.151	590	0.219
566	0.170	599	0.248
576	0.188	609	0.237
594	0.203	623	0.263
603	0.203	643	0.272
619	0.219	660	0.273
623	0.263	680	0.271
643	0.272	697	0.265

* Not shown in figure.

TABLE 1-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF ALUMINUM ALLOY 2024 (continued)

T	C _p	T	C _p	T	C _p
CURVE 16*		CURVE 17 (cont.)*		CURVE 19 (cont.)*	
373	0.220	587	0.228	545	0.152
383	0.224	601	0.240	558	0.167
393	0.224			571	0.198
408	0.227	CURVE 18*		583	0.220
418	0.229	373	0.220	603	0.235
433	0.229	387	0.222		
444	0.229	402	0.223	CURVE 20*	
454	0.232	411	0.225	378	0.222
463	0.240	424	0.224	388	0.224
474	0.242	435	0.224	398	0.225
484	0.237	443	0.232	413	0.225
490	0.232	454	0.239	427	0.231
496	0.228	464	0.247	440	0.244
509	0.218	472	0.261	449	0.261
519	0.200	478	0.266	459	0.274
529	0.185	483	0.249	475	0.270
537	0.170	488	0.236	487	0.255
549	0.157	500	0.232	499	0.241
556	0.167	512	0.228	512	0.231
566	0.183	522	0.213	522	0.209
575	0.204	534	0.191	531	0.189
583	0.223	542	0.168	542	0.164
592	0.239	554	0.155	556	0.164
607	0.248	564	0.169	567	0.191
		574	0.192	578	0.215
		582	0.216	582	0.240
		594	0.233	608	0.257
		609	0.244	620	0.266
				625	0.266
		CURVE 19*		646	0.275
		379	0.220	663	0.277
		388	0.222	677	0.272
		397	0.224	692	0.271
		413	0.224		
		433	0.231		
		447	0.236		
		459	0.248		
		463	0.260		
		472	0.273		
		477	0.263		
		486	0.247		
		498	0.237		
		508	0.225		
		519	0.215		
		527	0.196		
		536	0.172		

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of Aluminum Alloy 2024 were located in the literature. This alloy contains about 93 percent of Aluminum, and its specific heat and thermal linear expansion are very close to those of pure Aluminum. Therefore, the heat of fusion of $96 \pm 2 \text{ cal g}^{-1}$ of pure Aluminum reported by Hultgren et al. [19] may be adopted as the heat of fusion of Aluminum Alloy 2024.

d. Thermal Linear Expansion

There are 18 sets of experimental data available for the thermal linear expansion of Aluminum Alloy 2024. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 1-8. The experimental data are tabulated in Table 1-9 and partially shown in Figure 1-3.

Most of the measurements within the temperature range 293-650 K are for an alloy of type 24S, which is the previous designation for type Al-2024. There is one or two data sets for each alloy of the types T-3, T-4, and T-6. The recommended values shown in Figure 1-3 and tabulated in Table 1-7 agree well with all measurements. Since the agreement between various investigations is fairly good, it can be concluded that various heat treatments do not have any significant effect on this property. It is worth noting that the thermal expansion values for this alloy are very close to those for pure aluminum which is primarily due to the high aluminum content (94 wt. %) of this alloy. The uncertainty of the recommended values is within $\pm 5\%$. The recommended values above 700 K were extrapolated according to the general trend of the expansion curve for this alloy between 500 and 700 K and that for pure aluminum.

The values of the instantaneous coefficient of thermal linear expansion, α , are obtained by differentiation of empirical equations which are used to fit the recommended thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is within $\pm 10\%$.

The melting range for this alloy is 775-911 K. No experimental data for the thermal expansion or density of this alloy in the molten state were located in the literature. The values for the density given in Table 1-7 were calculated from the Kopp-Neumann mixing rule using the density values of constituent elements from TPRC Report 16 [27]. These density values are provisional and are considered accurate to within $\pm 7\%$.

TABLE 1-7 RECOMMENDED THERMAL LINEAR EXPANSION
OF ALUMINUM ALLOY 2024

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α	T	$\Delta L/L_0$	α
20	-0.428	8.7	273.15	-0.042	20.8
25	-0.420	8.8	293	0.000	21.6
30	-0.414	9.2	300	0.014	21.9
40	-0.407	9.8	350	0.127	23.7
50	-0.400	10.4	400	0.249	25.1
60	-0.390	10.9	450	0.378	26.4
70	-0.378	11.4	500	0.515	27.5
80	-0.367	12.0	550	0.655	28.4
90	-0.354	12.5	600	0.798	29.1
100	-0.340	13.1	650	0.946	29.7
150	-0.268	15.6	700	1.095	30.0
200	-0.184	17.9	750	1.245	30.1
250	-0.090	20.0	775 [†]	1.325	30.1

[†] Solidus Temperature.

PROVISIONAL DENSITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Density, d, g cm^{-3}]

T	d
911 [†]	2.446
1000	2.428
1100	2.408
1200	2.388
1300	2.368
1400	2.348
1500	2.328

[†] Liquidus Temperature.

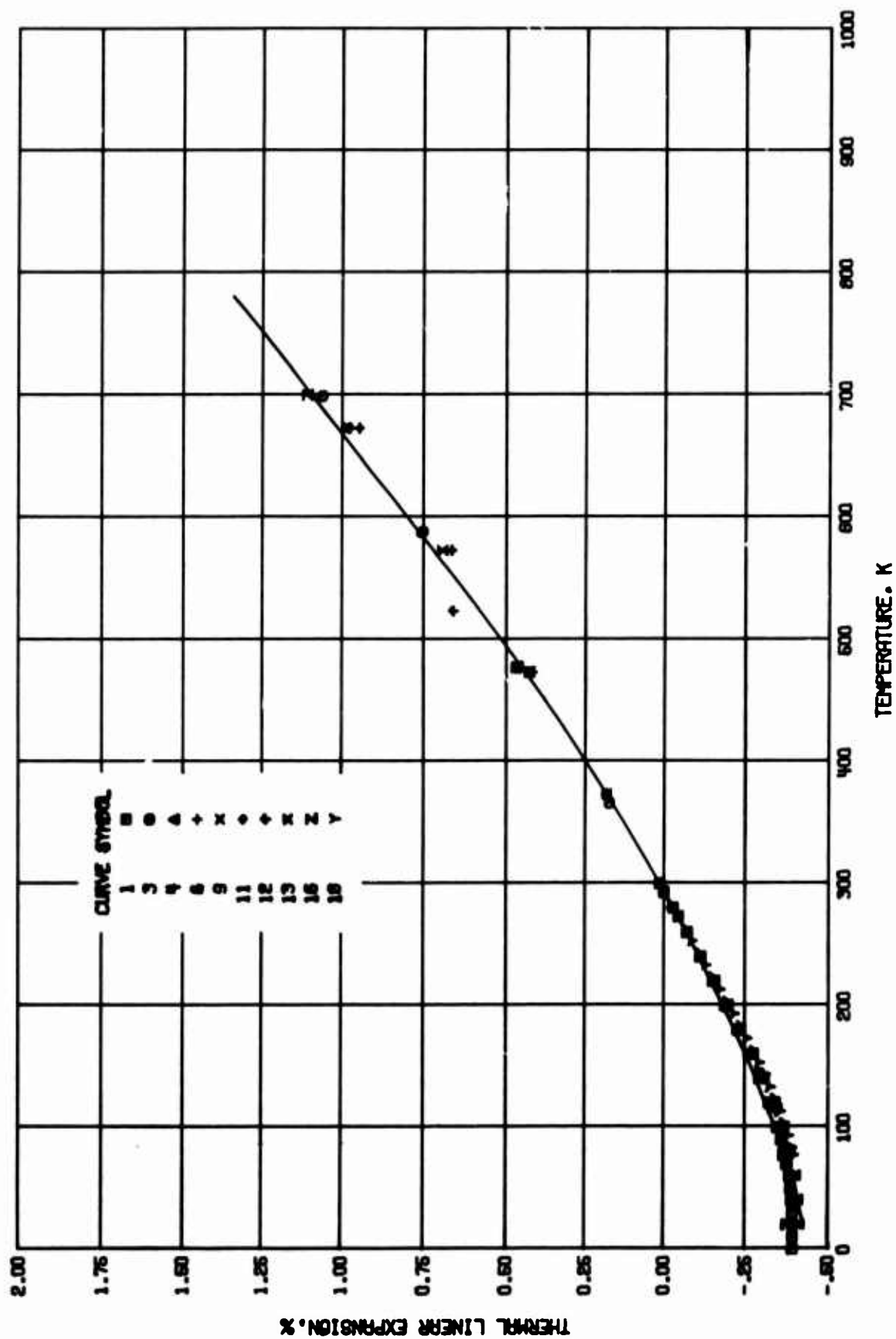


FIGURE 1-3. THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024.

TABLE 1-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Al	Cu	Composition (weight percent)				Mg	Ni	Composition (continued), Specifications, and Remarks
1	Clark, A. F.	1968	L	0-300		93.6	4.1	0.2	0.1	0.5	1.4			0.1 Zn; specimen machined to 20.32 cm long, 0.64 cm sq; Rockwell hardness B-25.
2*	Clark, A. F.	1968	L	0-300		Bal.	4.1	0.2						0.1 Zn; similar to the above specimen; Rockwell hardness B-83.
3	Lucks, C. F. and Deem, H. W.	1958	L	116-699	T4									0.375 in. diameter, 3 in. long; material from Aluminum Co. of America.
4	Arp, V., Wilson, J. H., and Winick, L., and Sikora, P.	1962	L	20-293		92.6	4.1	1.4	0.5	0.2	0.1	0.1		0.1 Zn; hardness R _g 83, A.S.M. condition T-86.
5*	Valentich, J.	1965	L	106-516										No details given; zero-point correction is -0.1%.
6	Hildert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10	0.67	1.41	0.01		0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; specimen solution heat treated 1 hr at 766 K, quenched in water and aged to room temperature; expansion measured with increasing temperature.
7*	Hildert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10					0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
8*	Hildert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10					0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; similar to the above specimen, then aged 100 hr at 644 K; expansion measured with increasing temperature.
9	Hildert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10					0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
10*	Hildert, P. and Krider, H. S.	1952	L	293-673	Al 24S	Bal.	4.41	0.25	0.10					0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; similar to the above specimen except aged 500 hr at 700 K; expansion measured with increasing temperature.
11	Hildert, P. and Krider, H. S.	1952	L	673-293	Al 24S	Bal.	4.41	0.25	0.10					0.02 Zn and 0.01 each Bi, Cr, Pb, Ti; the above specimen; expansion measured with decreasing temperature.
12	Willey, L. A. and Fink, W. L.	1945	I	293-573	Alcoa 24S		4.5	1.5	0.6					Sheet wrought form cold-rolled to 0.064 in. thick; tested in as-rolled condition.
13	Willey, L. A. and Fink, W. L.	1945	I	293-573	Alcoa 24S	Bal.	4.5			0.6	1.5			Similar to the above specimen except annealed to 623 K.
14*	Willey, L. A. and Fink, W. L.	1945	I	213-373	Alcoa 24S	Bal.	4.5							Similar to the above specimen except heat-treated and aged according to standard practice.
15*	Hertz, J.	1962		77-300	T-3									No details given; zero-point correction is 0.014%.

* Not shown in figure.

TABLE 1-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024 (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Al	Cu	Composition (weight percent)				Mg	Ni	Composition (continued), Specifications, and Remarks
16	34	Technology Utilization Div., NASA	1969		20-700	Al 2024-T6								Specimen prepared in accordance with Rockwell Materials and Processes Specifications or equivalent (government or ASTM); dilatometric measurements.
17*	34	Technology Utilization Div., NASA	1969		77-755	Al 2024-T4								Specimen prepared using the above specifications.
18	35	Belov, A. K.	1968	L	293-77									No details given.

* Not shown in figure.

TABLE 1-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF ALUMINUM ALLOY 2024
[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
<u>CURVE 1</u>		<u>CURVE 2 (cont.)*</u>		<u>CURVE 6 (cont.)</u>		<u>CURVE 13</u>	
0	-0.392	293	0.000	373	0.185	293	0.000
10	-0.392	300	0.015	473	0.421	373	0.182
20	-0.392			573	0.666	473	0.430
30	-0.391	<u>CURVE 3</u>		673	0.946	573	0.692
40	-0.389						
50	-0.386			<u>CURVE 7*</u>		<u>CURVE 14*</u>	
60	-0.382	116	-0.345	293	0.000	213	-0.172
70	-0.375	144	-0.294	373	0.179	293	0.000
80	-0.367	199	-0.194	473	0.423	373	0.186
90	-0.358	293	0.000	673	0.996		
100	-0.347	366	0.174			<u>CURVE 15*</u>	
120	-0.323	477	0.464			77	-0.371
140	-0.294	588	0.755			97	-0.351
160	-0.262	699	1.062			100	-0.341
180	-0.228	<u>CURVE 4</u>				109	-0.332
200	-0.191			293	0.000	118	-0.317
220	-0.153	20	-0.411	373	0.425	127	-0.304
240	-0.113	40	-0.408	573	0.686	137	-0.292
260	-0.071	60	-0.400	673	0.984	145	-0.273
273	-0.044	80	-0.385			158	-0.258
280	-0.029	100	-0.364	<u>CURVE 9</u>		178	-0.224
293	0.000	120	-0.338	293	0.000	186	-0.208
300	0.015	140	-0.308	373	0.182	196	-0.188
<u>CURVE 2*</u>		160	-0.275	473	0.427	207	-0.168
0	-0.396	180	-0.237	673	0.988	224	-0.133
10	-0.396	200	-0.198			235	-0.116
20	-0.396	220	-0.158	<u>CURVE 10*</u>		245	-0.096
30	-0.396	240	-0.116	293	0.000	252	-0.078
40	-0.394	260	-0.073	373	0.182	263	-0.060
50	-0.391	273	-0.044	473	0.422	272	-0.039
60	-0.387	280	-0.029	573	0.680	277	-0.026
70	-0.380	293	0.000	673	0.969	291	-0.007
80	-0.372	<u>CURVE 5*</u>				293	0.000
90	-0.363	106	-0.394			300	0.014
100	-0.351	166	-0.278	<u>CURVE 11</u>		<u>CURVE 16</u>	
120	-0.325	223	-0.153	673	0.980	20	-0.375
140	-0.295	293	0.000	473	0.430	77	-0.365
160	-0.262	347	0.132	373	0.184	477	0.470
180	-0.227	401	0.286	293	0.000	700	1.110
200	-0.190	450	0.413				
220	-0.151	516	0.583	<u>CURVE 12</u>		<u>CURVE 17*</u>	
240	-0.111			293	0.000	77	-0.373
260	-0.070	<u>CURVE 6</u>		373	0.182		
273	-0.043	293	0.000	473	0.419		
280	-0.028			523	0.661		

* Not shown in figure.

CURVE 18

293	0.000
283	-0.023
273	-0.045
263	-0.068
253	-0.090
243	-0.112
233	-0.134
223	-0.156
213	-0.177
203	-0.198
193	-0.219
183	-0.239
173	-0.258
163	-0.277
153	-0.295
143	-0.312
133	-0.327
123	-0.342
113	-0.356
103	-0.368
93	-0.380
83	-0.390
77	-0.396

e. Thermal Diffusivity

Ten sets of data, all measured within the temperature range 100 to 700 K, are available in the literature. The experimental data are tabulated in Table 1-12 and shown in Figure 1-4. The information on specimen characterization and measurement condition for the data sets is given in Table 1-11.

The recommended values were calculated from the equation:

$$\alpha = \frac{k}{C_p d}$$

where k is the thermal conductivity, C_p is the specific heat, and d is the density. The recommended values for k and C_p given in previous sections were used for the calculation, and the recommended thermal expansion values were used to derive density values as a function of temperature. The recommended values tabulated in Table 1-10 and shown in Figure 1-4 are for an as-received 2024-T4 alloy having a residual electrical resistivity of $3.2 \mu\Omega \text{ cm}$ and a room temperature density of 2.77 g cm^{-3} and for an annealed 2024 alloy having residual electrical resistivity of about $0.70 \mu\Omega \text{ cm}$. The recommended values for the as-received alloy agree with the data of Lucks et al. [20] (Curve 7) to within $\pm 12\%$. The data of Butler and Inn [36, 37] (Curves 1-6) exhibit a much weaker temperature dependence. This discrepancy is believed to be due to different heat treatments. It may be noted that the thermal diffusivity of the specimen measured by Butler and Inn increases after repeated heating to high temperatures. The recommended values for the annealed alloy agree with the data of Lucks et al. [20] (Curve 8) to within $\pm 8\%$.

The uncertainty of the recommended values is believed to be within $\pm 12\%$ at temperatures below 200 K and $\pm 8\%$ above.

**TABLE 1-10. RECOMMENDED THERMAL DIFFUSIVITY OF
ALUMINUM ALLOY 2024**

[Temperature, T, K; Thermal Diffusivity, α , $\text{cm}^2 \text{s}^{-1}$]

T	α	
	As received	Annealed
100	0.496	1.000
150	0.441	0.813
200	0.449	0.738
250	0.469	0.723
273.15	0.478	0.721
293	0.487	0.719
300	0.491	0.719
350	0.517	0.722
400	0.553	0.727
450	0.609	0.715
500	0.656	0.697
550	0.665	0.677
600	0.654	0.656
650	0.634	0.634
700	0.612	0.612
750	0.583	0.583
775	0.568	0.568

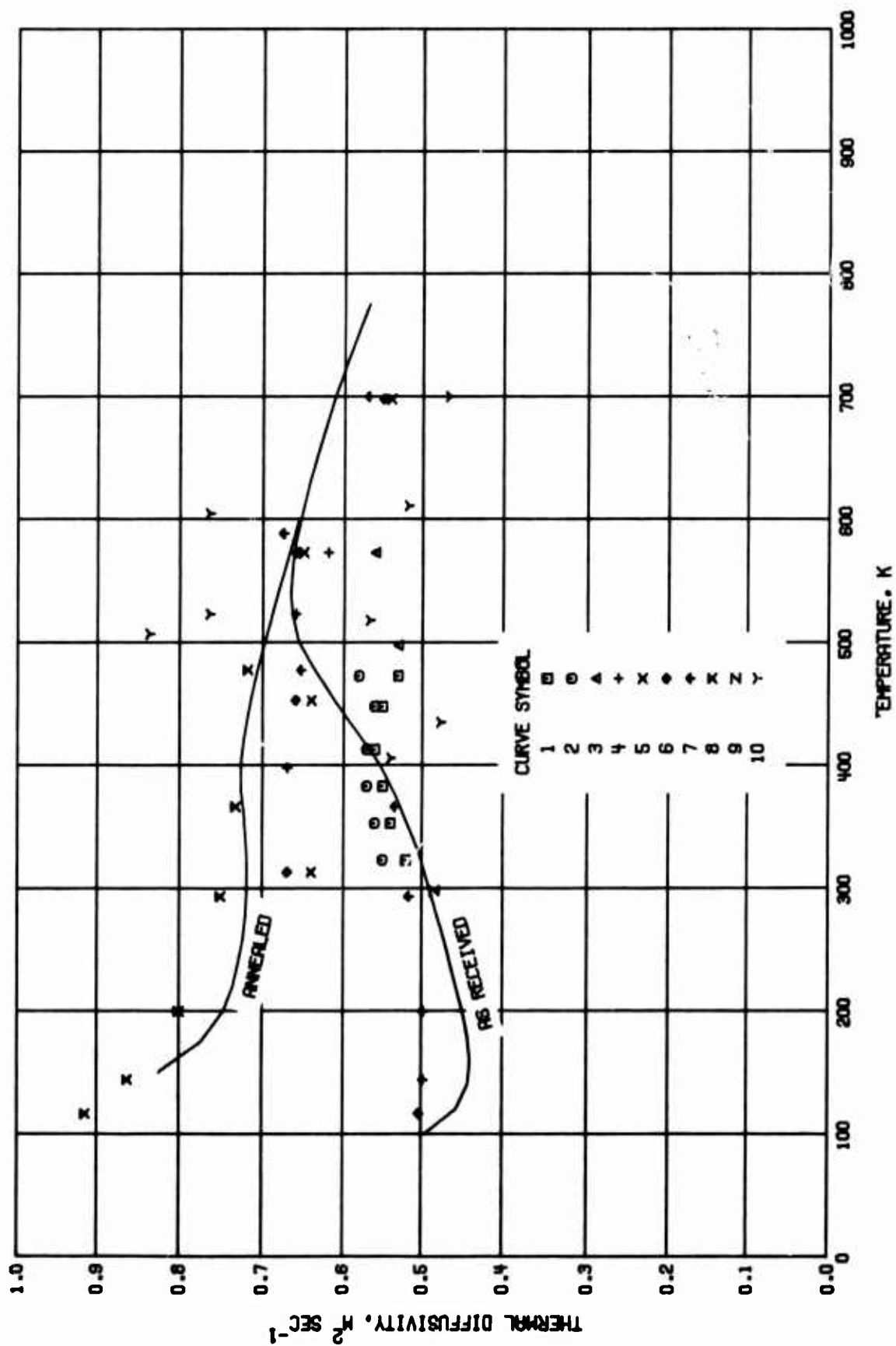


FIGURE 1-4. THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024 .

TABLE 1-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Al	Cu	Cr	Fe	Mg	Mn	Si	Zn	Composition (continued), Specifications, and Remarks
1 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	323-473	2024-T86	~	3.8/ 4.9	0.10 max	0.50 max	1.2/ 1.8	0.30/ 0.9	0.50 max	0.25 max	90.90-93.20 Al (by difference), and 0.15 max others; nominal composition from Alcoa Aluminum Handbook, p. 44, 1962; cylindrical specimen 0.9525 cm in diameter and length lying in the range from 1 to 2.5 cm; nominal heat treatment (from above source): solution heat treatment, strain hardening, and then artificial aging; subjected to irradiance from carbon arc lamp heat source; spectral distribution approximates that of a 5700 K black body source; specimen blackened with camphor black; measured under a vacuum of ~5 microns; reported error 5-10%.
2 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	323-473	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
3 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	388-573	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
4 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	398-573	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
5 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	313-698	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
6 36, 37	Butler, C. P. and Ina, E. C. Y.	1957	T	313-698	2024-T86									Same as the above specimen allowed to cool to ambient and then exposed to the arc lamp to measure diffusivity again.
7 6, 20	Lucks, C. F., Deem, H. W., Thompson, H. B., Smith, A. R., Curry, F. P., and Bing, G. F.	1951		116-700	2024-T4		4.5		1.5	0.6				Supplied by Aluminum Co. of America; condition as received T4 (solution heat treatment followed by natural aging at room temperature to a substantially stable condition); thermal diffusivity calculated from measured conductivity, specific heat, and density.
8 6, 20	Lucks, C. F., et al.	1951		116-700	2024-T4									Same as the above alloy measured again for thermal conductivity after being heated above 574.8 K; thermal diffusivity calculated from measured conductivity, specific heat, and density.
9 38	Tomsic, M.	1969	P	298	2024-T6		4.5		1.5	0.6				Nominal composition; cylindrical specimen; measuring temperature assumed 25 C.
10 39	Cushman, J. B., Jr.	1964	T	406-700	2024-T4									1 in. diameter by 4 in. long; measured by a modified Jominy and Quench method.

TABLE 1-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF ALUMINUM ALLOY 2024

[Temperature, T, K; Thermal Diffusivity, α , cm² s⁻¹]

T	α	T	α
<u>CURVE 1</u>		<u>CURVE 7 (cont.)</u>	
323.2	0.52	199.8	0.498
353.2	0.54	293.2	0.516
383.2	0.55	366.4	0.534
413.2	0.56	477.6	0.653
448.2	0.55	586.7	0.674
473.2	0.53	699.8	0.568
<u>CURVE 2</u>		<u>CURVE 8</u>	
323.2	0.55	116.4	0.914
353.2	0.56	144.2	0.862
383.2	0.57	199.8	0.800
413.2	0.57	293.2	0.751
448.2	0.56	366.4	0.733
473.2	0.58	477.6	0.718
<u>CURVE 3</u>		586.7	0.674
386.2	0.55	699.8	0.568
448.2	0.56	<u>CURVE 9</u>	
498.2	0.53	298	0.485
573.2	0.56	<u>CURVE 10</u>	
<u>CURVE 4</u>		406	0.539
396.2	0.67	435	0.477
523.2	0.66	507	0.835
573.2	0.62	518	0.566
<u>CURVE 5</u>		523	0.764
313.2	0.64	605	0.764
453.2	0.64	611	0.517
573.2	0.65	700	0.466
698.2	0.54	<u>CURVE 6</u>	
<u>CURVE 6</u>		313.2	0.67
313.2	0.67	453.2	0.64
453.2	0.64	573.2	0.66
573.2	0.66	698.2	0.55
<u>CURVE 7</u>		<u>CURVE 7</u>	
116.4	0.503	116.4	0.503
144.2	0.498	144.2	0.498

3.2. AISI 304 Stainless Steel

The family of steels known as "stainless steels" covers a wide range of composition. About 35 to 40 different combinations of ingredients have been used by various manufacturers. Primarily all stainless steels have chromium as the major alloying element. The nominal composition of AISI 304 Stainless is 18.00-20.00% Cr, 8.00-10.50% Ni, 2.00% (max.) Mn, 1.00% (max.) Si, 0.08% (max.) C, 0.045% (max.) P, 0.030% (max.) S, and balance Fe. The composition of 304L is essentially the same except that the carbon content is lowered to 0.03% (max.).

Chromium, when added to iron in excess of 10%, makes the alloy heat and corrosion resistant. Other elements are added to obtain special characteristics. The most important of these in the case of stainless steels is nickel which increases the corrosion resistance and workability of the alloy. This addition causes a structural change which is known as austenitic, making the alloy nonhardenable and nonmagnetic. It is possible to weld AISI 304 stainless in moderate thickness without requiring subsequent heat treatment to restore corrosion resistance.

Various properties and uses of this alloy are discussed in detail in [1]. Some of the physical properties are summarized as follows:

Density:	7.9 g cm ⁻³
Melting range:	1670-1727 K
Electrical resistivity at room temperature:	72 $\mu\Omega$ cm
Modulus of elasticity in tension:	28 x 10 ⁶ psi
Modulus of elasticity in torsion:	12.5 x 10 ⁶ psi

a. Thermal Conductivity

Thirty-three sets of experimental data are available, mostly measured between room temperature and 1200 K. All the measurements are for specimens in solid state, including some for porous samples. The experimental data are tabulated in Table 2-3 and shown partially in Figure 2-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 2-2.

The recommended values for the thermal conductivity of AISI 304 stainless steel are given in Table 2-1 and shown in Figure 2-1. The values below 100 K are for a steel having residual electrical resistivity of about 48.4 $\mu\Omega$ cm. At cryogenic temperatures the values are based on the data of Stutius and Dillinger [40] (curve 28). Above 25 K

the values follow the data of Powers et al. [41] (curve 5), Moeller [42] (curves 10-13), Deverall [43] (curve 1), Taylor et al. [44] (curve 15), Moeller and Finch [45] (curves 10-13), and Tye et al. [46] (curve 32) to 1200 K. Above 1200 K the recommended values are extrapolated.

The solidus and liquidus temperatures of AISI 304 stainless steel are around 1670 and 1727 K, and no thermal conductivity values are recommended in this region. In molten state from 1800 to 2000 K, the recommended values are calculated from the equation:

$$k = \frac{LT}{\rho}$$

where the Lorenz number L is taken as $L_0 (=2.443 \times 10^{-8} \text{ V}^2 \text{ K}^{-2})$ and the electrical resistivity ρ is obtained from [47] for an Fe + 10% Ni alloy, which in the solid state has the same ρ values as AISI 304. The values of ρ and L used in the calculations are certainly different from the true values for the 304 stainless steel, thereby contributing major portion of the uncertainty to the recommended thermal conductivity values for the molten steel.

The uncertainty of the recommended values is estimated to be within $\pm 10\%$ below 25 K, $\pm 5\%$ from 25 to 1200 K, and $\pm 10\%$ between 1200 and 1600 K. The values for the molten steel are provisional, with an estimated uncertainty of about $\pm 20\%$.

TABLE 2-1. RECOMMENDED THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Thermal Conductivity, k, $\text{W cm}^{-1} \text{K}^{-1}$]

T	k	T	k
4	0.00288	500	0.183
7	0.00531	550	0.191
10	0.00796	600	0.198
15	0.0129	650	0.205
20	0.0183	700	0.212
25	0.0241	750	0.219
30	0.0304	800	0.226
40	0.0438	850	0.233
50	0.0566	900	0.240
60	0.0675	950	0.247
70	0.0750	1000	0.254
80	0.0810	1100	0.267
90	0.0869	1200	0.280
100	0.0919	1300	0.293
150	0.111	1400	0.305
200	0.126	1500	0.317
250	0.138	1600	0.327
273.15	0.143	1670 [†]	0.333
293	0.147	1727 [†]	0.288
300	0.149	1800	0.294
350	0.158	1900	0.304
400	0.166	2000	0.315
450	0.175		

[†] Approximate melting range.

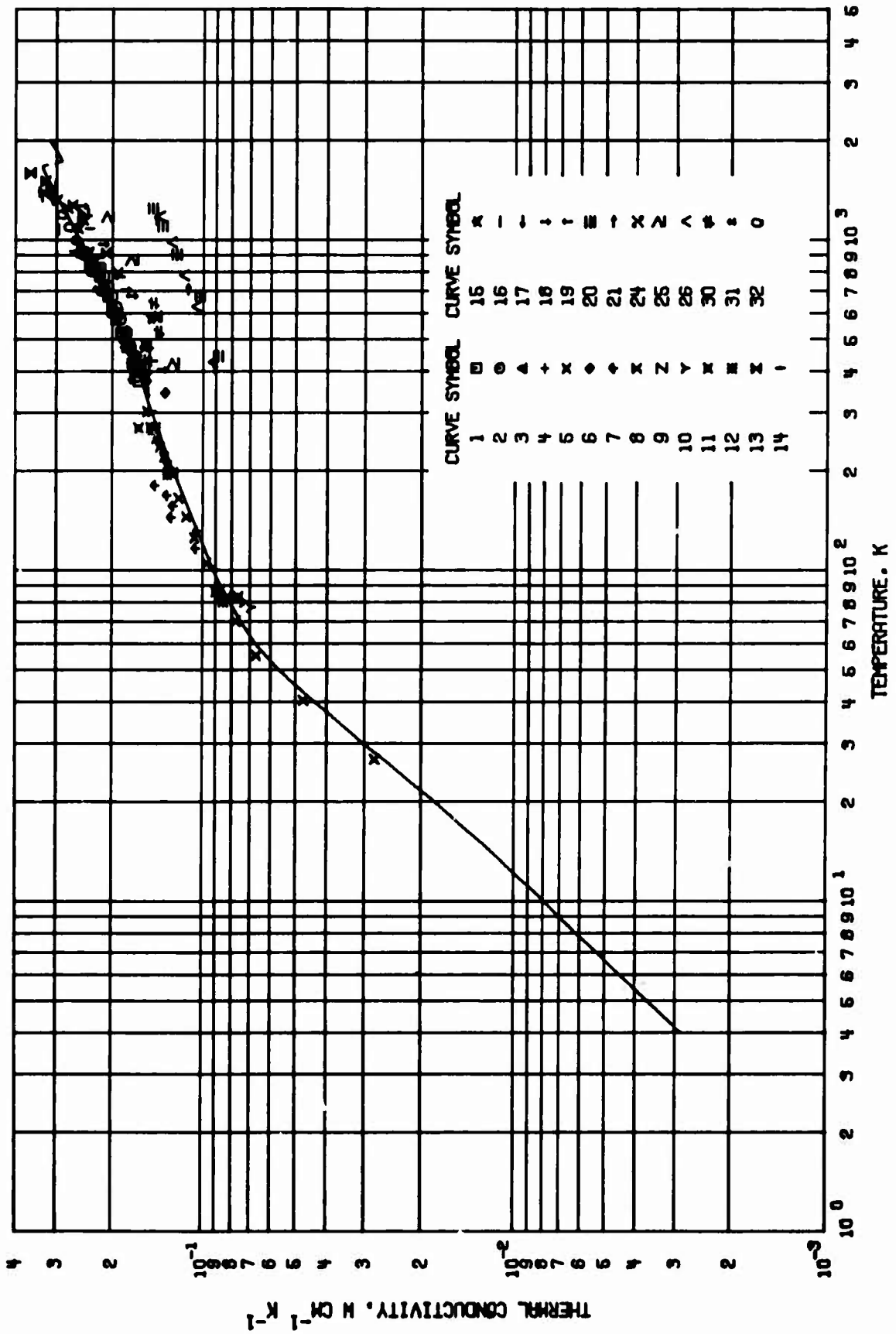


FIGURE 2-1. THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Fe	Cr	Ni	C	Mn	Si	Composition (continued), Specifications, and Remarks
1 43	Deverall, J.E.	1959	L	373-773		18.51	18.51	9.09	0.053	0.67	0.53	0.028 S and 0.025 P; 1 in. diameter by 14.25 in. long; measured in an insulated guarded apparatus; smoothed values reported; reported error 5.6%.
2 43	Deverall, J.E.	1959	L	423-823		18.51	18.51	9.09	0.053	0.67	0.53	Same material as the above specimen; 0.75 in. diameter by 10 in. long; measured in a vacuum apparatus; smoothed values reported. Nominal composition; 1.625 in. in diameter.
3 48	Ewing, C.T., Grand, J.A., and Miller, R.R.	1952	L	473-916		18.0/20.0	8.0/11.0	<0.08	<0.08	<2.0		
4 48	Ewing, C.T., et al.	1952	L	470-926		18.0/20.0	8.0/11.0	<0.08	<0.08	<2.0		The above specimen.
5 41	Powers, R.W., Ziegler, J.B., and Johnston, H.L.	1951	L	27-250		18.68	8.84	0.05	1.12	0.43		0.06 Cu, 0.031 N, 0.023 S, and 0.017 P; supplied by Carnegie Illinois Steel Corp.
6 49	Brophy, J.H. and Simcoe, M.J.	1960	R	344-482		18/20	8/12	<0.08	<2.0	<1.00		<0.045 P and <0.03 S (nominal composition); disk-like specimens 2.75 in. O.D.
7 50	Smith, C.F.	1963	L	100-180		18/20	8/12	<0.08	<2.00	<1.00		<0.045 P and <0.030 S (nominal composition); 0.144 in. diameter by 10.125 in. long; machined; measured in a vacuum of $<5 \times 10^{-5}$ mm Hg.
8 51, 52	Feith, A.D., Hein, R.A., Johnstone, C.P., and Flagella, P.N.	1968	R	795-1593		Bal.	18.37	9.89	0.024	1.31	0.70	0.09 Mo, 0.05 Cu, 0.041 P, and 0.012 S; specimen ~0.95 cm I.D., ~5.04 cm O.D., and 1.25 cm thick; centerless ground, fully annealed; electrical resistivity reported as 72.31, 74.42, 79.29, 90.88, 91.07, 94.31, 97.99, 102.45, 105.05, 109.48, 112.46, 111.86, 113.82, 119.06, 123.29, 127.0, 130.57, 130.42, 130.62, 130.53, 131.32, 130.59, and 132.47 $\mu\Omega$ cm at 26, 46, 111, 265, 279, 311, 373, 442, 522, 583, 657, 697, 755, 854, 1031, 1169, 1255, 1328, 1339, 1345, 1354, 1361, and 1378 C, respectively; reported error $\pm 6-8\%$.
9 51, 52	Feith, A.D., et al.	1968	P	791-1590		Bal.	18.37	9.89	0.024	1.31	0.70	Similar to the above specimen except thermal conductivity values calculated from the measurements of thermal diffusivity (using the average data of 2 specimens 0.635 cm in diameter, one 0.127 cm thick, and another 0.152 cm thick) and enthalpy of specimens fabricated from the same raw material as used for the thermal conductivity; reported values obtained from smooth curve; reported error $\pm 5\%$.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent)					Composition (continued), Specifications, and Remarks
							Fe	Cr	Ni	C	Mn	
10	42, 45	Moeller, E. and Finch, H. L.	1969	L	77-871		18/20	8/12	<0.08	<2.00	<1.00	<0.045 P and <0.030 S (nominal composition); specimen 1.27 cm in diameter and 2.54 cm long; reported error $\pm 5\%$.
11	42, 45	Moeller, E. and Finch, H. L.	1969	L	83-270		18/20	8/12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 10.2 cm in diameter and 7.6 cm long.
12	42, 45	Moeller, E. and Finch, H. L.	1969	L	80-270		18/20	8/12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 5.1 cm in diameter and 6.6 cm long.
13	42, 45	Moeller, E. and Finch, H. L.	1969	L	83-267		18/20	8/12	<0.08	<2.00	<1.00	Similar to the above specimen except specimen 5.1 cm in diameter and 7.6 cm long.
14	44, 53	Taylor, R.E., Powell, R.W., Nalbandyan, M., and Davis, F.	1968	E	923-1082		18/20	8/12	<0.08	<2.00	<1.00	<0.045 P and <0.030 S (nominal composition); specimen 7 in. long; heated at 1050 C for 2 hr at 10^{-4} torr; measured in a vacuum of $\sim 10^{-4}$ torr; thermal conductivity data calculated by using Krishnan and Jain's method; reported error $\pm 1.5\%$.
15	44, 53	Taylor, R.E., et al.	1968	E	912-1081		18/20	8/12	<0.08	<2.00	<1.00	The above specimen; thermal conductivity data calculated by using Lebedev's method; reported error $\pm 2.5\%$.
16	44, 53	Taylor, R.E., et al.	1968	E	763-1072		18/20	8/12	<0.08	<2.00	<1.00	The above specimen; thermal conductivity data calculated by using Taylor's method.
17	54	Brown, W.T., Jr. and Bergles, A.E.	1968	E	345-527		18.00/20.00	8.00/12.00	<0.08	<2.00	<1.00	Nominal composition; tube specimen 0.2518 in. in O.D., 0.1243 in. in I.D., and 4.88 in. long; electrical resistivity 69.3, 71.1, 71.9, 74.5, 76.8, 79.5, 82.3, 83.8 and 86.2 $\mu\Omega$ /cm at 311, 338, 349, 369, 422, 465, 509, 532, and 575 K respectively.
18	55	Tye, R. P.	1970	C	404-1264		18.00/20.00	8.00/12.00	<0.03	<2.00	<1.00	Nominal composition; 63.9 x 63.8 x 20.6 mm; electrical resistivity 92.6, 100, 117, 130, 140.5, 148.5, and 152 $\mu\Omega$ /cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 9.5%; heat flow perpendicular to the weave pattern; measured in vacuum from 3×10^{-3} to 2×10^{-4} torr; Inconel used as comparative material.
19	55	Tye, R. P.	1970	C	428-1182		18.00/20.00	8.00/12.00	<0.03	<2.00	<1.00	The above specimen measured in a nitrogen atm.
20	55	Tye, R. P.	1970	C	442-1243		18.00/20.00	8.00/12.00	<0.03	<2.00	<1.00	Nominal composition; 64.6 x 64.4 x 26.19 mm; electrical resistivity 147.5, 159, 187, 208.5, 225, 237.5, and 243 $\mu\Omega$ /cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 20.3%; heat flow perpendicular to the weave pattern; measured in vacuum from 5×10^{-3} to 6×10^{-4} torr; Inconel used as comparative material.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Fe	Cr	Ni	C	Mn	%	Composition (continued), Specifications, and Remarks
21 55	Tye, R. P.	1970	C	406-1151		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		The above specimen measured in a nitrogen atm.
22* 55	Tye, R. P.	1970	C	518-1216		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		Nominal composition; 62.75 x 62.59 x 24.46 mm; electrical resistivity 300, 327, 384, 424, 451, 478, and 492 $\mu\Omega$ cm at 22, 100, 300, 500, 700, 900, and 1000 C, respectively; porosity 38.5%; heat flow perpendicular to the weave pattern; measured in vacuum from 2×10^{-5} to 3×10^{-4} torr; Inconel used as comparative material.
23* 55	Tye, R. P.	1970	C	415-1168		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		The above specimen measured in a nitrogen atm.
24 56	Tye, R. P.	1973	C	412-1083		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		Nominal composition; 2.54 cm diameter by 2.54 cm long; electrical resistivity 72.0, 78.8, 93.0, 104.5, 112, and 116.5 $\mu\Omega$ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; Inconel 702 used as comparative material; reported error <10%.
25 56	Tye, R. P.	1973	C	421-1173		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		Fabricated from sintered spherical powder particles obtained from 304L stainless steel stock; 2.56 cm diameter by 2.53 cm thick; electrical resistivity 95, 112, 122, 135, 146, and 157 $\mu\Omega$ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 9.2%; Inconel 702 used as comparative material.
26 56	Tye, R. P.	1973	C	425-1176		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		Same fabrication and measuring methods as the above specimen; 2.56 cm diameter by 2.54 cm thick; electrical resistivity 135, 147.5, 175, 195, 213, and 231 $\mu\Omega$ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 21.38%.
27* 56	Tye, R. P.	1973	C	472-1178		18.00-20.00	8.00-12.00	<0.03	<2.00	<1.00		Same fabrication and measuring methods as the above specimen; 2.54 cm diameter by 2.52 cm thick; electrical resistivity 230, 250, 291, 315, 332, and 338 $\mu\Omega$ cm at 293, 373, 573, 773, 973, and 1173 K, respectively; porosity 31.0%.
28* 40	Stutins, W. and Dillinger, J. R.	1973	L	0.39-1.7		18-20	8-12	<0.08	<2	<1		Nominal composition; 0.6 cm diameter by 4 cm long; electrical resistivity 47.1, 47.6, and 76.2 $\mu\Omega$ cm at 4.2, 77, and 295 K, respectively; Néel temperature >295 K.
29* 40	Stutins, W. and Dillinger, J. R.	1973	L	0.45-1.5		18-20	8-12	<0.03	<2	<1		Similar to the above specimen except electrical resistivity 49.9, 50.6, and 70.4 $\mu\Omega$ cm at 4.2, 77, and 295 K, respectively.

* Not shown in figure.

TABLE 2-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF AISI 304 STAINLESS STEEL (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent)					Composition (continued), Specifications, and Remarks
						Fe	Cr	Ni	C	Mn	
30	Bondi, P. and Ferro, V.	1967	L	401-641		18-20	8-10	≤0.08	≤2	≤1	Nominal composition; reported error 3%.
31	Bondi, P. and Ferro, V.	1967	L	712, 813		18-20	8-10	≤0.08	≤2	≤1	Nominal composition; plate specimen; reported error 3%.
32	Tye, R. P., Hayden, R. W., and Spinney, S. C.	1972	L	300-1200	Bal.	18.49	8.61	0.051	1.69	0.40	0.21 Cu, 0.21 Mo, 0.12 Co, and 0.029 S (nominal composition); 12.7 mm diameter by 100 mm long; annealed; density 7.900-7.920 g cm ⁻³ ; electrical resistivity 46.7, 71.7, 79.1, 86.2, 92.7, 98.7, 104.0, 108.0, 112.2, 115.5, and 118.5 μΩ cm at 4.2, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.
33*	Careaga, J. A., Mayer, E. R., and Del Castillo, L.	1970	L	89-207		18-20	8-12	≤0.08	≤2	≤1	Nominal composition (from Metals Handbook); cylindrical specimen.

* Not shown in figure.

TABLE 2-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF STAINLESS STEEL 304 (continued)

T	k	T	k
CURVE 29 (cont.)*		CURVE 33 (cont.)*	
0.869	0.000556	197.9	0.137
0.929	0.000604	207.4	0.141
0.982	0.000649		
1.02	0.000658		
1.10	0.000698		
1.19	0.000753		
1.29	0.000791		
1.39	0.000843		
1.51	0.000927		
CURVE 30			
401	0.155		
423	0.155		
477	0.153		
526	0.141		
579	0.150		
641	0.147		
CURVE 31			
712	0.224		
813	0.221		
CURVE 32			
300	0.1490		
400	0.1665		
500	0.184		
600	0.202		
700	0.218		
800	0.234		
900	0.247		
1000	0.261		
1100	0.275		
1200	0.289		
CURVE 33*			
89.0	0.0586		
105.1	0.0705		
113.3	0.0740		
124.4	0.0805		
133.2	0.0830		
140.5	0.0785		
161.9	0.100		
172.3	0.114		
187.9	0.133		

* Not shown in figure.

b. Specific Heat

There are seven sets of experimental data available for the specific heat of AISI 304 Stainless Steel. One data set (curve 4) which is for a Russian 1Kh18N9T steel having similar composition is also included. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 2-5. The experimental data is tabulated in Table 2-6 and shown in Figure 2-2.

With the exception of the first two curves, the measurements were carried out within the temperature range 295-1623 K. The recommended values shown in Figure 2-2 and tabulated in Table 2-4 are derived primarily from the investigation of Feith et al. [51, 59] (curve 3) and also using the specific heat data for other 300 series stainless steels. The specific heat data of Lyusternik [60] (curve 4) for a Russian steel of type 1Kh18N9T agree well (0-5% lower) with the recommended values. The specific heat values calculated using the Kopp-Neumann mixing rule also agree well except in the region 800-1200 K, where the phase transformation of Fe occurs. The heat content data of Neel et al. [61] (curve 7) are about 25% higher, while those of Smith [62] (curve 6) show a wide scatter resulting in about 10-20% higher specific heat values. The specific heat data of Venuti and Seibel [63] (curve 5) are about 25% lower than the recommended values. It is worth noting that the selected specific heat values for pure iron [19] are within $\pm 5\%$ of the specific heat values for this steel except in the phase transformation region 1100-1200 K. The uncertainty of the recommended values is about $\pm 5\%$.

The melting region of this steel is 1670-1727 K. No experimental data for the specific heat of this or any other similar steel in the molten state were located in the literature. Considering the agreement between the experimental data and the calculated values for the solid steel from the Kopp-Neumann mixing rule, the provisional values for the molten steel tabulated in Table 2-4 were calculated using the above procedure. In the calculation the specific heat values for constituent elements in the molten state were taken from Hultgren et al. [19]. Selected values for pure iron in the molten state [19] are about 2% higher than the provisional values for the steel. The uncertainty of the provisional values is $\pm 10\%$.

TABLE 2-4. RECOMMENDED SPECIFIC HEAT OF
AISI 304 STAINLESS STEEL

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p
100	0.065
150	0.082
200	0.096
250	0.106
273.15	0.110
293	0.113
300	0.114
350	0.119
400	0.123
450	0.126
500	0.129
550	0.131
600	0.133
650	0.135
700	0.136
750	0.138
800	0.139
850	0.140
900	0.142
950	0.144
1000	0.146
1100	0.149
1200	0.153
1300	0.156
1400	0.159
1500	0.163
1600	0.166
1670†	0.169
1727†	0.194‡
1800	0.194‡
2000	0.194‡

† Approximate melting range.

‡ Provisional value.

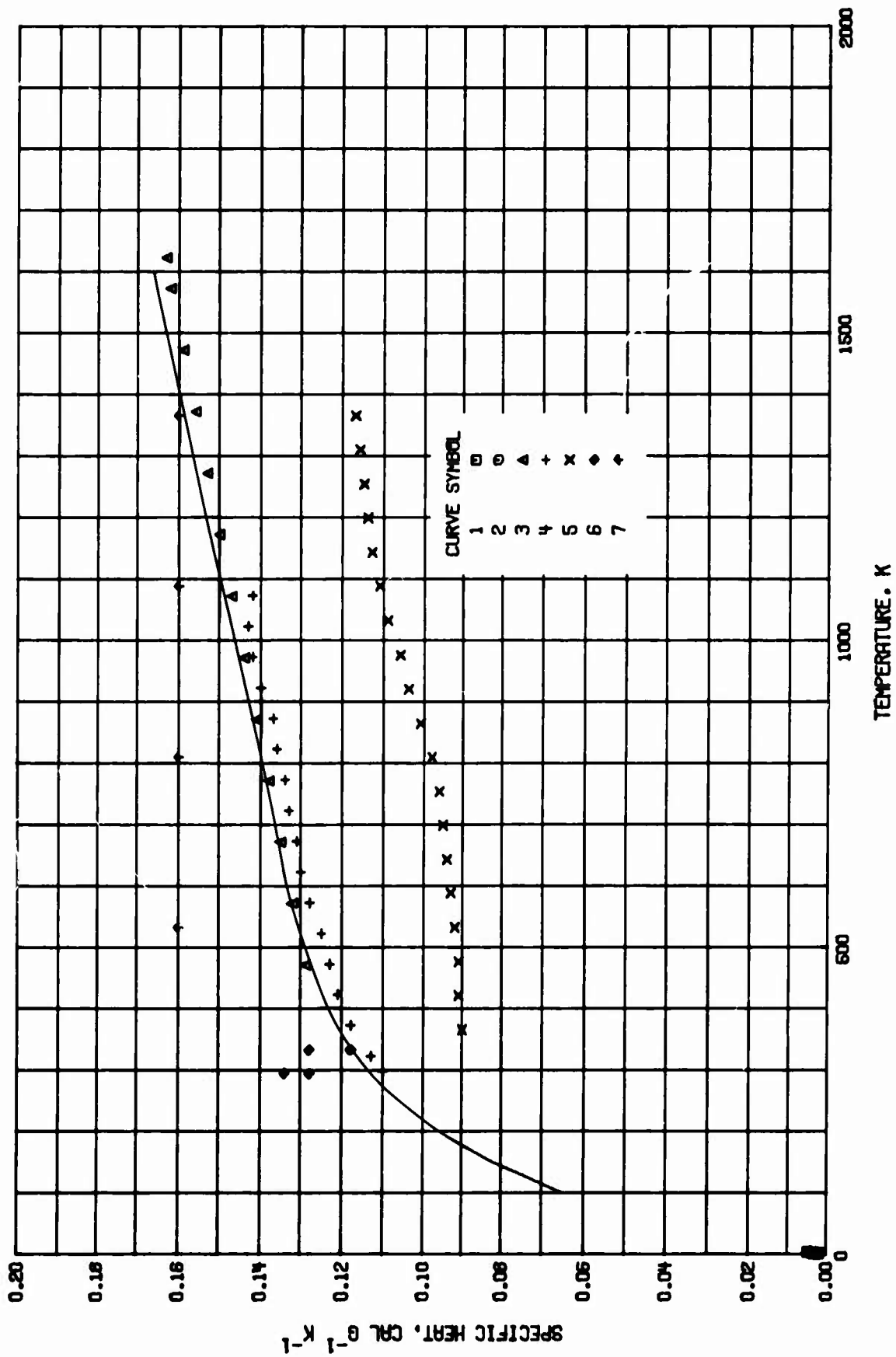


FIGURE 2-2. SPECIFIC HEAT OF AISI 304 STAINLESS STEEL.

TABLE 2-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF AISI 304 STAINLESS STEEL

[illegible]

TABLE 2-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p	T	C_p
<u>CURVE 1</u>		<u>CURVE 5</u>	
1.7	0.0019	366	0.090
2.0	0.0022	422	0.091
3.0	0.0033	477	0.091
4.2	0.0048	533	0.092
<u>CURVE 2</u>		589	0.093
1.7	0.0017	644	0.094
2.0	0.0020	700	0.095
3.0	0.0031	755	0.096
4.2	0.0044	811	0.098
<u>CURVE 3</u>		866	0.101
473	0.129	922	0.104
573	0.132	977	0.106
673	0.135	1033	0.109
773	0.138	1089	0.111
873	0.141	1144	0.113
973	0.144	1200	0.114
1073	0.147	1255	0.115
1173	0.150	1311	0.116
1273	0.153	1366	0.117
1373	0.156	<u>CURVE 6</u>	
1473	0.159	295	0.128
1573	0.162	295	0.134
1623	0.163	333	0.128
<u>CURVE 4</u>		333	0.118
298	0.110	<u>CURVE 7</u>	
323	0.113	533	0.160
373	0.116	811	0.160
423	0.121	1089	0.160
473	0.123	1366	0.160
523	0.125		
573	0.128		
623	0.130		
673	0.131		
723	0.133		
773	0.134		
823	0.136		
873	0.137		
923	0.140		
973	0.142		
1023	0.143		
1073	0.142		

c. Heat of Fusion

No experimental data were located in the literature. However, a value of $60 \pm 5 \text{ cal g}^{-1}$ for the heat of fusion of iron reported by Hultgren, Desai, Hawkins, Gleiser, Kelley, and Wagman [19] may be used as a very rough estimate.

d. Thermal Linear Expansion

There are nine sets of experimental data available for thermal linear expansion of AISI 304 stainless steel. The information on the specimen characterization and measurement condition for each data set is given in Table 2-8. The experimental data are tabulated in Table 2-9 and shown partially in Figure 2-3.

Among these, three data sets (curves 1, 5, and 8) were measured at temperatures below room temperature and others cover the range 293 to 1667 K. The recommended values shown in Figure 2-3 and tabulated in Table 2-7 agree well with most of the measurements with the exception of the data of Conway and Flagella [65] (curve 9) which are about 8% higher above 800 K. The uncertainty of the values is about $\pm 5\%$ below 1300 K and $\pm 10\%$ above.

The melting range for this steel is 1670–1727 K. No experimental values for the density of this steel in the molten state are located in the literature. Since the melting point of this steel is considerably high, estimations of densities from the Kopp-Neumann mixing rule or any other techniques are highly uncertain and also not possible due to lack of experimental density data for constituent elements in that temperature range.

The values of the instantaneous coefficient of thermal linear expansion, α , are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about $\pm 10\%$ below 1300 K and $\pm 15\%$ above.

TABLE 2-7. RECOMMENDED THERMAL LINEAR EXPANSION
OF AISI 304 STAINLESS STEEL.

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α
20	-0.339	9.8
25	-0.336	9.9
30	-0.331	10.0
40	-0.319	10.2
50	-0.308	10.4
60	-0.298	10.6
70	-0.287	10.8
80	-0.277	11.0
90	-0.265	11.2
100	-0.254	11.4
150	-0.195	12.4
200	-0.130	13.2
250	-0.061	14.1
273.15	-0.031	14.4
293	0.000	14.7
300	0.011	14.9
350	0.086	15.6
400	0.167	16.3
450	0.251	16.9
500	0.338	17.5
550	0.427	18.0
600	0.519	18.6
650	0.612	19.0
700	0.709	19.5
750	0.807	19.9
800	0.907	20.2
850	1.007	20.4
900	1.112	20.6
950	1.217	20.8
1000	1.323	21.1
1100	1.536	21.3
1200	1.748	21.4
1300	1.959	21.4
1400	2.171 [‡]	21.4 [‡]
1500	2.386 [‡]	21.5 [‡]
1600	2.601 [‡]	21.6 [‡]
1670	2.753 [‡]	21.7 [‡]

[‡] Provisional value.

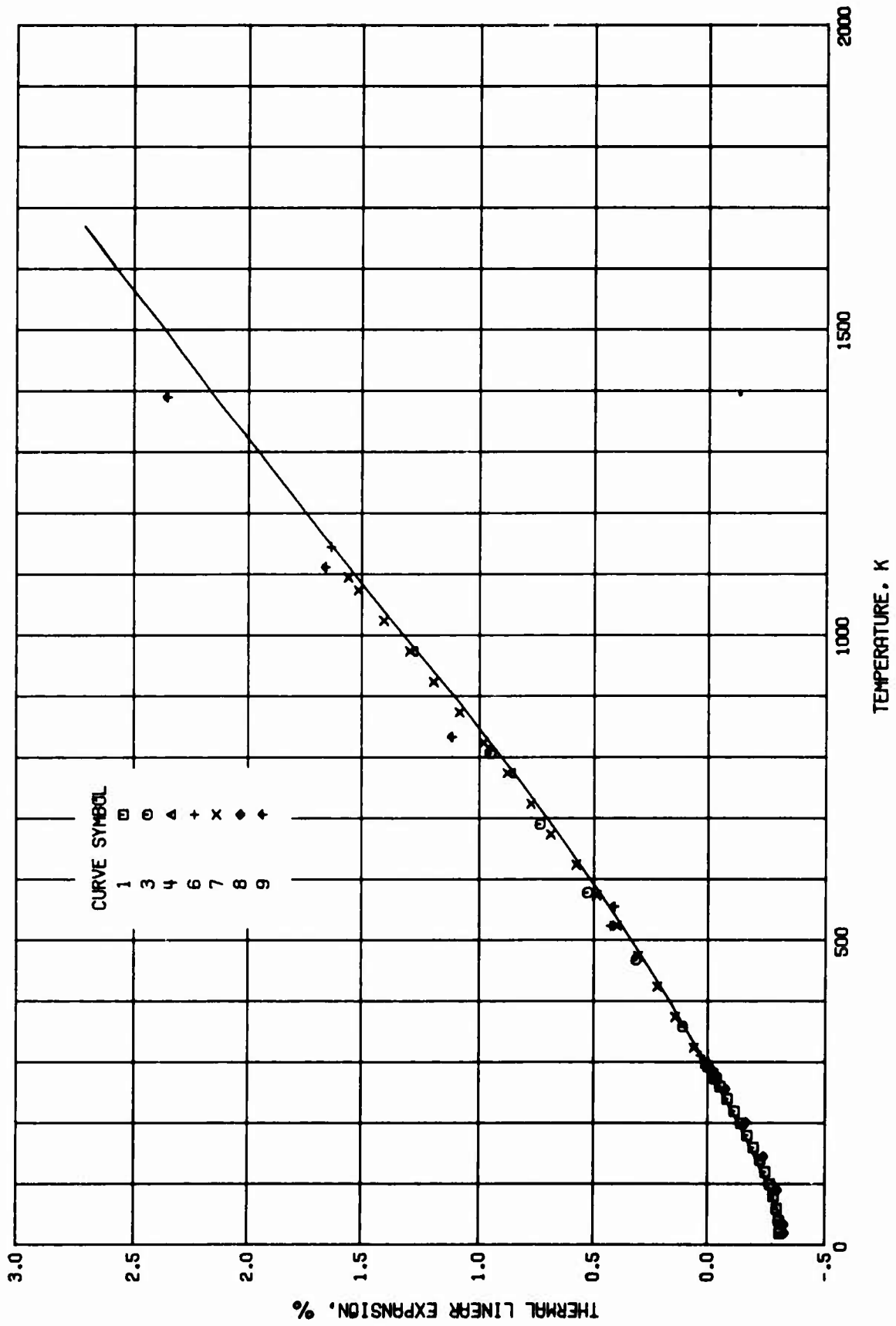


FIGURE 2-3. THERMAL LINEAR EXPANSION OF AISI 304 STAINLESS STEEL .

TABLE 2-8. MEASUREMENT INFORMATION ON THE LINEAR THERMAL EXPANSION OF AISI 304 STAINLESS STEEL

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent)	Composition (continued), Specifications, and Remarks
						Fe Cr Mn Si C Ni P	
1 29	Arp, V., Wilson, J. H., Winick, L., and Sikora, P.	1962	L	20-293	304 L	Bal. 18.4 1.4 0.6 0.02 9.7 0.02	0.01 S; hardness Rp 94; annealed specimen.
1* 66	Furman, D.E.	1950		89-810	304 ss	Bal. 19.19 0.65 0.53 0.068 8.49 0.024	0.007 S; 0.250 in. diameter by 4.0 in. long; prior to machining, the expansion specimen of commercial grade steel annealed at 1338 K for 30 min., then water quenched.
3 30	Valentich, J.	1965	L	293-806	304 ss		No details given.
4 67	Yaggee, F.L., Gilbert, E.R., and Styles, J.W.	1969	L	273-973	AISI Type 304 ss		Commercial grade alloy containing 950 ppm interstitials, 6.4 mm O.D. rod.
5* 68	Benakker, J.J.M. and Swenson, C.A.	1955	L	0-300			Technical grade alloy.
6 69	Martin, W.R. and Weir, J.R.	1961	L	310-1144			No details given.
7 70	Droege, J.W.	1972		293-1094			No details given.
8 34	Technology Utilization Div., NASA	1969	L	19-293	304 L CRES		Specimen prepared in accordance with Rocketdyne Materials and Processes Specifications or equivalent; annealed at 1950 F and water quenched.
9 65	Cosway, J.B. and Flagella, P.N.	1968		298-1667	304 L		Data of Fieldhouse, et al.; zero-point correction is 0.005%.

* Not shown in figure.

TABLE 2-9. EXPERIMENTAL DATA ON THE LINEAR THERMAL EXPANSION OF AISI 304 STAINLESS STEEL
[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 1				CURVE 2 (cont.)*			
20	-0.306	244	-0.076	630	0.588	523	0.427
40	-0.303	250	-0.071	644	0.614	811	0.958
60	-0.294	255	-0.058	658	0.636	1144	1.636
80	-0.281	261	-0.046	672	0.667	CURVE 7	
100	-0.265	267	-0.040	686	0.695	293	0.000
120	-0.245	272	-0.029	700	0.724	298	0.013
140	-0.222	278	-0.024	714	0.741	323	0.060
160	-0.195	283	-0.013	728	0.768	373	0.141
180	-0.168	289	-0.005	742	0.809	423	0.219
200	-0.140	294	0.002	755	0.831	473	0.305
220	-0.113	300	0.012	769	0.858	523	0.399
240	-0.083	305	0.018	783	0.887	573	0.489
260	-0.052	311	0.028	797	0.917	623	0.577
273	-0.031	317	0.037	810	0.945	673	0.691
290	-0.021	322	0.044	CURVE 3		723	0.777
293	0.000	328	0.055	293	0.000	773	0.882
CURVE 2*				358	0.109	823	0.983
89	-0.271	333	0.073	468	0.314	873	1.087
94	-0.263	344	0.082	578	0.527	923	1.194
100	-0.257	350	0.091	690	0.737	973	1.295
105	-0.248	355	0.100	806	0.954	1023	1.405
111	-0.243	361	0.107	CURVE 4		1073	1.515
117	-0.238	367	0.118	273	-0.036	1094	1.561
122	-0.231	372	0.128	773	0.968	CURVE 8	
128	-0.225	378	0.134	973	1.282	19	-0.327
133	-0.217	383	0.145	CURVE 5*		33	-0.325
139	-0.213	389	0.151	0	-0.263	89	-0.295
144	-0.206	394	0.161	25	-0.263	144	-0.237
150	-0.201	400	0.172	50	-0.262	200	-0.162
155	-0.192	405	0.182	75	-0.252	255	-0.075
161	-0.184	411	0.191	100	-0.232	287	-0.015
167	-0.177	417	0.199	125	-0.205	293	0.000
172	-0.172	422	0.207	150	-0.175	CURVE 9	
178	-0.168	436	0.236	175	-0.142	298	0.008
183	-0.160	450	0.259	200	-0.108	555	0.408
189	-0.152	464	0.281	275	-0.038	833	1.118
194	-0.143	478	0.309	300	0.042	1111	1.658
200	-0.140	492	0.334	CURVE 6		1369	2.358
205	-0.130	505	0.358	310	0.031	1667	3.008
211	-0.126	519	0.383				
217	-0.114	533	0.402				
222	-0.104	547	0.429				
228	-0.095	561	0.455				
233	-0.089	575	0.484				
239	-0.083	589	0.507				
		603	0.536				
		617	0.563				

* Not shown in figure.

e. Thermal Diffusivity

Ten sets of experimental data, all measured within the temperature range 290 to 1400 K, are available in the literature. These experimental data are tabulated in Table 2-12 and shown in Figure 2-4. The information on specimen characterization and measurement condition for the data sets is given in Table 2-11.

The recommended values for AISI 304 stainless steel with residual electrical resistivity of approximately $48.4 \mu\Omega$ cm were calculated from the formula

$$\alpha = \frac{k}{C_p d}$$

where k is the thermal conductivity, C_p is the specific heat, and d is the density. The recommended thermal conductivity and specific heat values given in previous sections were used directly for the calculations and the recommended thermal linear expansion values were used to derive density values as a function of temperature. The recommended values tabulated in Table 2-10 and shown in Figure 2-4 agree to within $\pm 8\%$ with the data of Feith et al. [52] (curves 5 and 6).

The uncertainty of the recommended values for the solid steel is estimated to be within $\pm 10\%$. The values for the molten steel are provisional with a probable uncertainty of $\pm 20\%$.

TABLE 2-10. RECOMMENDED THERMAL DIFFUSIVITY OF AISI 304 STAINLESS STEEL

[Temperature, T, K; Thermal Diffusivity, α , $\text{cm}^2 \text{s}^{-1}$]

T	α
100	0.0417
150	0.0400
200	0.0389
250	0.0386
273.15	0.0386
293	0.0387
300	0.0388
350	0.0396
400	0.0403
450	0.0416
500	0.0426
550	0.0439
600	0.0450
650	0.0460
700	0.0473
750	0.0483
800	0.0497
850	0.0510
900	0.0520
950	0.0529
1000	0.0538
1100	0.0558
1200	0.0578
1300	0.0593
1400	0.0610
1500	0.0623
1600	0.0635
1670 [†]	0.0639
1727 [†]	0.0481
1800	0.0491
1900	0.0507
2000	0.0526

[†] Approximate melting range.

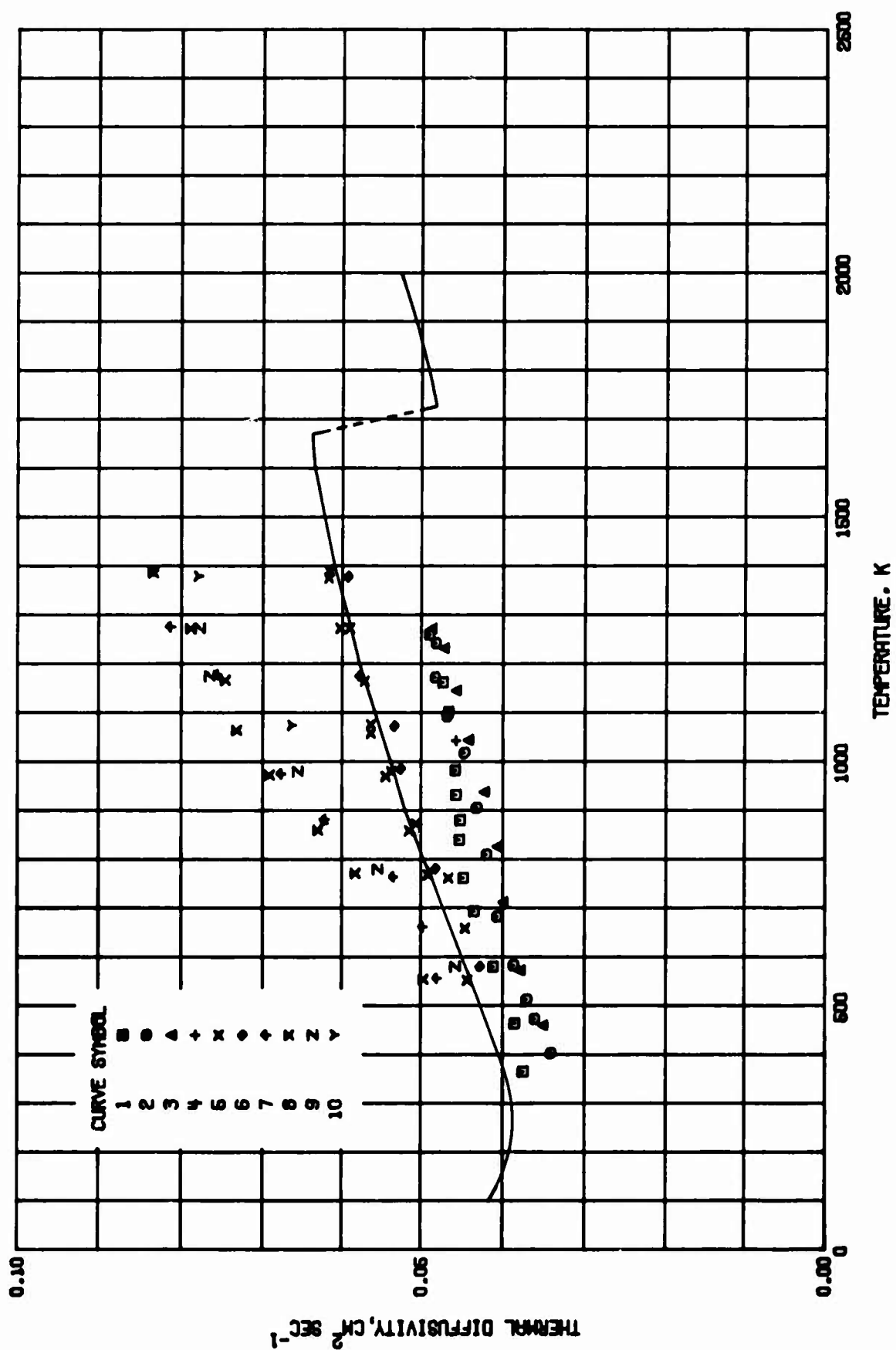


FIGURE 2-4. THERMAL DIFFUSIVITY OF AISI 304 STAINLESS STEEL.

TABLE 2-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF STAINLESS STEEL 304

[Temperature, T, K; Thermal Diffusivity, α , cm² s⁻¹]

T	α	T	α	T	α
<u>CURVE 1</u>		<u>CURVE 5</u>		<u>CURVE 9</u>	
291	0.0356	552	0.0443	580	0.0458
366	0.0376	658	0.0446	780	0.0555
465	0.0386	762	0.0466	980	0.0657
581	0.0412	768	0.0492	1176	0.0766
695	0.0435	859	0.0515	1273	0.0778
763	0.0448	873	0.0507	<u>CURVE 10</u>	
841	0.0453	970	0.0545	874	0.0624
981	0.0452	980	0.0538	1075	0.0664
933	0.0457	1058	0.0564	1380	0.0779
983	0.0458	1076	0.0564		
1103	0.0466	1165	0.0572		
1163	0.0473	1273	0.0591		
1261	0.0490	1273	0.0603		
		1376	0.0618		
		1390	0.0617		
<u>CURVE 2</u>		<u>CURVE 6</u>			
403	0.0342	580	0.0428		
473	0.0362	781	0.0482		
513	0.0372	966	0.0526		
583	0.0387	1073	0.0534		
683	0.0407	1176	0.0578		
810	0.0420	1379	0.0593		
906	0.0432				
1018	0.0447				
1083	0.0468				
1173	0.0483				
1243	0.0482				
<u>CURVE 3</u>		<u>CURVE 7</u>			
460	0.0352	556	0.0480		
573	0.0380	662	0.0498		
713	0.0400	764	0.0535		
827	0.0407	882	0.0622		
938	0.0423	975	0.0678		
1045	0.0442	1178	0.0756		
1146	0.0457	1276	0.0813		
1233	0.0472	1391	0.0833		
1273	0.0487				
<u>CURVE 4</u>		<u>CURVE 8</u>			
		554	0.0497		
		772	0.0583		
		860	0.0631		
		973	0.0692		
		1065	0.0732		
		1167	0.0746		
		1273	0.0789		
		1387	0.0833		
1043	0.0457				

3.3. Pyroceram (Corning 9606)

Pyroceram is a generic name for a group of microcrystalline glass-ceramic materials, which were developed by the Corning Glass Works, Corning, New York 14830.

Pyroceram brand glass-ceramic Code 9606 (Corning 9606) is a magnesia aluminosilicate glass-ceramic (composed of silicon dioxide, aluminum oxide, magnesium oxide, and a small amount of titanium dioxide). The ingredients are melted together at a temperature of the order of 1900 K using special techniques to insure uniform composition, constant density, freedom from bubbles and striations, and uniform electrical properties. Corning Pyroceram 9606 is non-porous, considerably harder than glass, opaque, and gray in color.

Corning Pyroceram 9606 is primarily used in military products and specifically as missile radomes since it has uniform electrical properties at elevated temperatures and the ability to pass R. F. signals. Other properties which make it useful for radome applications are good thermal shock and rain erosion characteristics.

According to Corning Pyroceram 9606 Data Sheets [75], its physical properties include softening point of 1623 K, density of 2.6 g cm^{-3} , porosity (void volume) of 0.00%, water absorption of 0.00%, and being impermeable to gas. Mechanical properties of Corning 9606 include strength to weight ratio (modulus of rupture to specific gravity) of $13.5 \times 10^3 \text{ psi}$ at 293 K, Young's modulus of $17.4 \times 10^6 \text{ psi}$ at 293 K, shear modulus of $6.9 \times 10^6 \text{ psi}$ at 293 K, Poisson's ratio of 0.245 at 293 K, modulus of rupture of $35 \times 10^3 \text{ psi}$ at 293 K, Knoop hardness of 619 kg mm^{-2} with a 500 gram load, and Knoop hardness of 698 kg mm^{-2} with a 100 gram load. Electrical properties include loss factor of 0.8% at 293 K and dielectric strength of $350 \text{ V rms mil}^{-1}$ at 293 K and 60 cps.

a. Thermal Conductivity

Twelve sets of experimental data are available. Three of these are single points. No measurement was made between 4 and 100 K. The experimental data are tabulated in Table 3-3 and shown in Figure 3-1. The information on specimen characterization and measurement condition for each of the data sets is given in Table 3-2.

The recommended values tabulated in Table 3-1 and shown in Figure 3-1 are based on the data of Flynn [76] (curve 4) and Robinson and Flynn [77] (curves 7-9). According to Flynn, annealing has no effect on the thermal conductivity of Corning Pyroceram 9606. The uncertainty of the recommended values is within $\pm 10\%$.

TABLE 3-1. RECOMMENDED THERMAL CONDUCTIVITY OF
PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Conductivity, k, $\text{W cm}^{-1} \text{K}^{-1}$]

T	k
100	0.0525
110	0.0549
120	0.0560
130	0.0556
150	0.0544
200	0.0478
250	0.0428
273.15	0.0413
293	0.0402
300	0.0398
350	0.0379
400	0.0364
450	0.0353
500	0.0343
550	0.0335
600	0.0328
650	0.0322
700	0.0317
750	0.0312
800	0.0308
850	0.0304
900	0.0300
950	0.0298
1000	0.0296
1100	0.0291
1200	0.0287
1300	0.0284
1400	0.0281
1500	0.0279
1600	0.0277

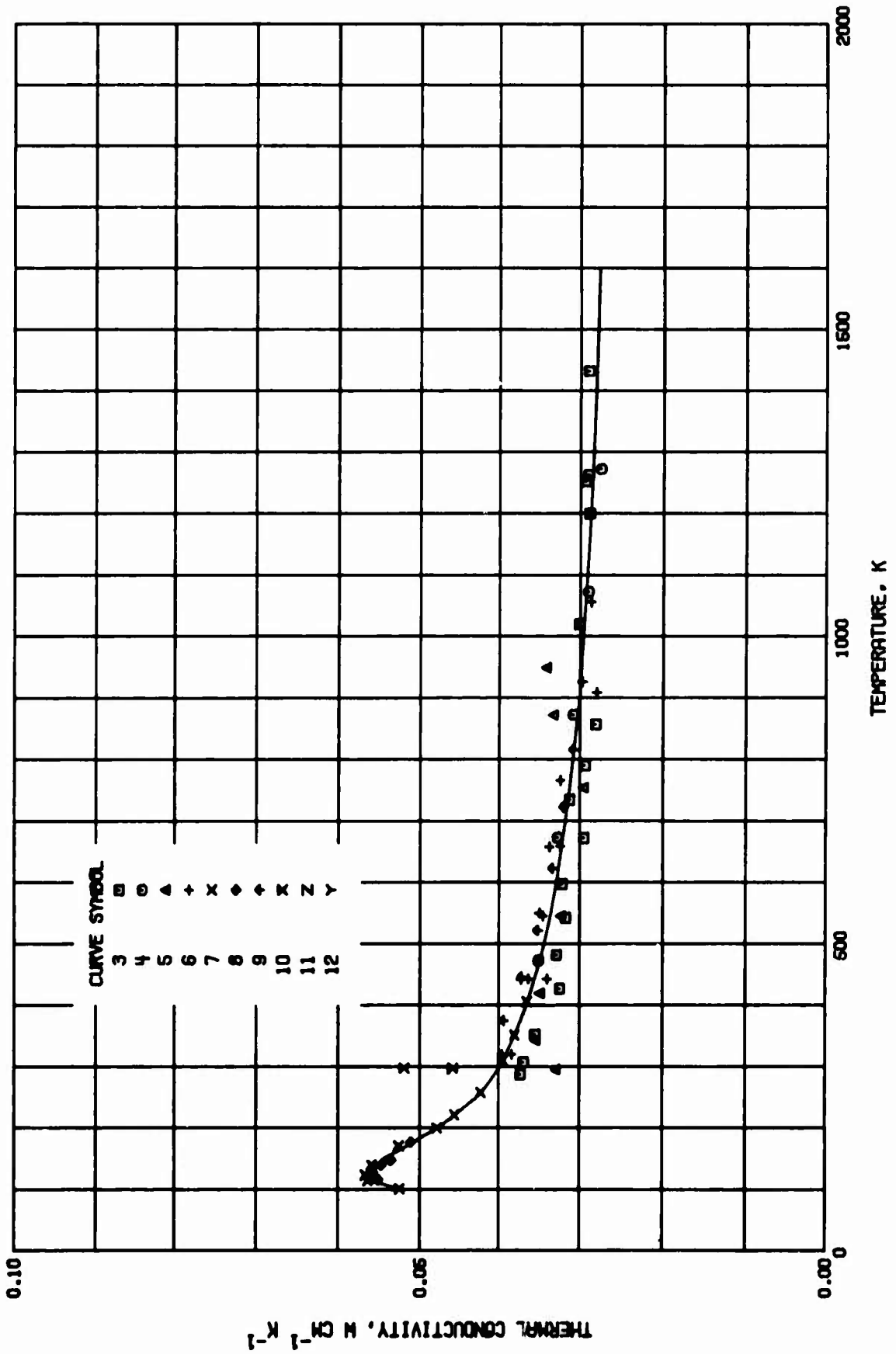


FIGURE 3-1. THERMAL CONDUCTIVITY OF PYROCERA (CORNING 9606) .

TABLE 3-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1* 78	Chang, G. K. and Jones, R. E.	1962	L	2.7-3.9		From Corning Glass Works; specimen cross-section 0.034 cm x 1.666 cm.
2* 78	Chang, G. K. and Jones, R. E.	1962	L	1.6-3.9		From Corning Glass Works; specimen cross-section 0.130 cm x 1.607 cm.
3 79	Ruckin, R. L.	1963	P	298-1433		From Corning Glass Works; calculated from thermal diffusivity data.
4 76, 80	Flynn, D. R., and Robinson, H. E.	1962	L	473-1273		Pyroceram 9606 (a microcrystalline glass), product of Corning Glass Works; specimen 2.540 cm in diameter and 1.269 cm in length; density 2.601 g cm^{-3} ; data obtained before and after the specimen held at 1000 C for about 275 hr agree with each other.
5 81	Braman, R. S.	1962	L	295-950		Specimen 2 in. long.
6 82, 83	Biemert, W. B., Trimmer, D. S., and Strabek, E. A.	1966	L	320-1057		Cylindrical shape specimen between 1/4 and 1/2 in. diameter and up to 1/2 in. long.
7 77, 84	Flynn, D. R., Robinson, H. E., and Marts, I. L.	1964	L	101-474		4.4 cm diameter x 31 cm long; diatomaceous earth used as insulation material; data taken from smooth curve.
8 77, 84	Flynn, D. R., et al.	1964	L	101-177		The above specimen; opacified silica aerogel used as insulation material; data taken from smooth curve.
9 77, 84	Flynn, D. R., et al.	1964	L	375-927		The above specimen measured in a high temperature apparatus; data taken from smooth curve.
10 85	Peggs, I. D. and Mills, R. W.	1970	P	298		0.437 cm diameter x 0.025 cm thick.
11 85	Peggs, I. D. and Mills, R. W.	1970	P	298		0.472 cm diameter x 0.025 cm thick.
12 85	Peggs, I. D. and Mills, R. W.	1970	P	298		0.467 cm diameter x 0.057 cm thick

* Not shown in figure.

TABLE 3-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹]

T	k	T	k	T	k
<u>CURVE 1*</u>		<u>CURVE 5</u>		<u>CURVE 9</u>	
2.65	0.0027	295	0.0329	375	0.0393
2.74	0.0029	343	0.0354	446	0.0370
3.16	0.0041	420	0.0349	522	0.0351
3.56	0.0053	546	0.0323	623	0.0333
3.94	0.0068	755	0.0296	723	0.0319
		873	0.0333	816	0.0307
<u>CURVE 2*</u>		950	0.0342	927	0.0297
1.56	0.0012	<u>CURVE 6</u>		<u>CURVE 10</u>	
1.59	0.0011	320	0.0396	298	0.052
1.90	0.0017	320	0.0383	<u>CURVE 11</u>	
2.10	0.0020	442	0.0371	298	0.046
2.43	0.0029	443	0.0362	<u>CURVE 12</u>	
2.67	0.0039	443	0.0340	298	0.046
2.91	0.0045	546	0.0345	<u>CURVE 12</u>	
3.18	0.0057	550	0.0349	298	0.046
3.45	0.0067	658	0.0337		
3.70	0.0080	659	0.0323		
3.91	0.0090	766	0.0323		
<u>CURVE 3</u>		769	0.0324		
289	0.0372	909	0.0280		
306	0.0368	1057	0.0287		
353	0.0354	<u>CURVE 7</u>			
428	0.0324	101	0.0526		
483	0.0328	114	0.0564		
543	0.0317	124	0.0567		
598	0.0321	140	0.0559		
673	0.0295	171	0.0527		
735	0.0312	200	0.0479		
791	0.0294	221	0.0457		
858	0.0281	258	0.0423		
1021	0.0301	310	0.0394		
1201	0.0289	351	0.0379		
1253	0.0294	406	0.0364		
1263	0.0290	474	0.0349		
1433	0.0290	<u>CURVE 8</u>			
		101	0.0526		
		116	0.0551		
		118	0.0557		
		128	0.0558		
		140	0.0547		
		148	0.0536		
		177	0.0512		
		<u>CURVE 4</u>			
		473	0.0350		
		673	0.0327		
		873	0.0308		
		1073	0.0290		
		1273	0.0275		

* Not shown in figure.

b. Specific Heat

There is only one data set available for the specific heat of Pyroceram 9606. The measurement was carried out at the Corning Glass Works [86] (curve 1). The information on the specimen characterization and measurement condition is given in Table 3-5. The experimental data are tabulated in Table 3-6 and shown in Figure 3-2.

The provisional values shown in Figure 3-2 and tabulated in Table 3-4 are derived from the above measurement. Above 1300 K the values are extrapolated. The uncertainty of the provisional values is about $\pm 7\%$ below 1300 K and about $\pm 15\%$ above that temperature.

TABLE 3-4. PROVISIONAL SPECIFIC HEAT OF
PYROCERAM (CORNING 9606)

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p
300	0.193
350	0.206
400	0.217
450	0.226
500	0.234
550	0.242
600	0.248
650	0.254
700	0.260
750	0.264
800	0.268
850	0.273
900	0.278
950	0.282
1000	0.286
1050	0.291
1100	0.294
1150	0.298
1200	0.302
1250	0.308
1300	0.316
1400	0.336
1500	0.358
1600	0.383

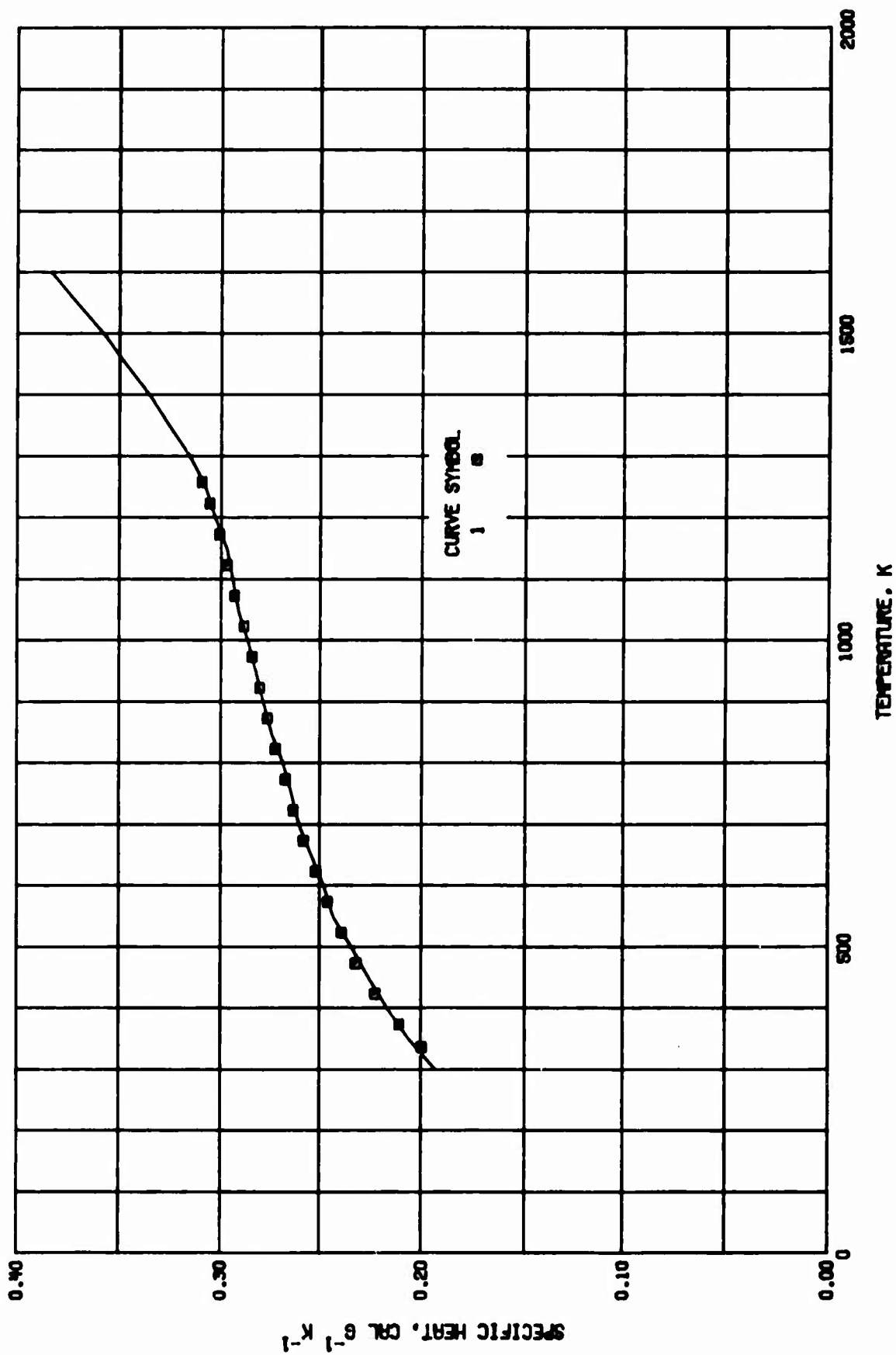


FIGURE 3-2. SPECIFIC HEAT OF PYROCERA (CORNING 9606) .

TABLE 3-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF PYROCERAM (CORNING 9606)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 86	Corning Glass Works	1958		336-1258		Hard, fine-grained crystalline material formed from special glasses; density 2.6 g cm ⁻³ .

TABLE 3-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Specific Heat, C_p, cal g⁻¹ K⁻¹]

T	$\Delta L/L_0$	CURVE 1	
		T	$\Delta L/L_0$
336	0.200	1173	0.301
373	0.211	1222	0.306
423	0.223	1258	0.310
473	0.232		
523	0.239		
573	0.246		
623	0.252		
673	0.258		
723	0.263		
773	0.267		
823	0.272		
873	0.276		
923	0.280		
973	0.284		
1023	0.288		
1073	0.293		
1123	0.297		

c. Heat of Fusion

No experimental data for the heat of fusion of Pyroceram (Corning 9606) or any comparable material were located in the literature. Corning Glass Works [86] reported a value of 1623 K for the softening point of this material.

d. Thermal Linear Expansion

There is only one set of data available for thermal linear expansion of Pyroceram (Corning 9606). The measurement was carried out at the Corning Glass Works [86] (curve 1). The information on the specimen characterization and measurement condition is given in Table 3-8. The experimental data are tabulated in Table 3-9 and shown in Figure 3-3. The provisional values shown in Figure 3-3 and tabulated in Table 3-7 are derived from the above measurement. It is worth noting that Corning Glass Works [86] (curve 1) found an anomaly of an unexplainable nature near 300 K. Their specific heat and conductivity measurements on a similar material fail to show such anomaly. The uncertainty of the provisional values is $\pm 10\%$.

The values of the instantaneous coefficient of thermal linear expansion, α , are obtained both from the α values reported by the Corning Glass Works [86] and by differentiation of empirical equations which are used to fit the thermal linear expansion data. The values at and above 400 K are provisional and their uncertainty is $\pm 15\%$, and those below 400 K are typical values which are very uncertain.

TABLE 3-7 PROVISIONAL THERMAL LINEAR EXPANSION
OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α
293	0.000	1.9 [‡]
300	0.002	2.5 [‡]
325	0.010	5.2 [‡]
350	0.023	6.9 [‡]
400	0.061	7.6
450	0.095	5.4
500	0.114	3.6
550	0.132	3.7
600	0.150	3.8
650	0.169	3.9
700	0.189	3.9
750	0.208	4.0
800	0.229	4.1
850	0.250	4.2
900	0.272	4.2
950	0.293	4.3
1000	0.314	4.4
1100	0.358	4.6
1200	0.401	4.7
1300	0.441	4.8

[‡] Typical value.

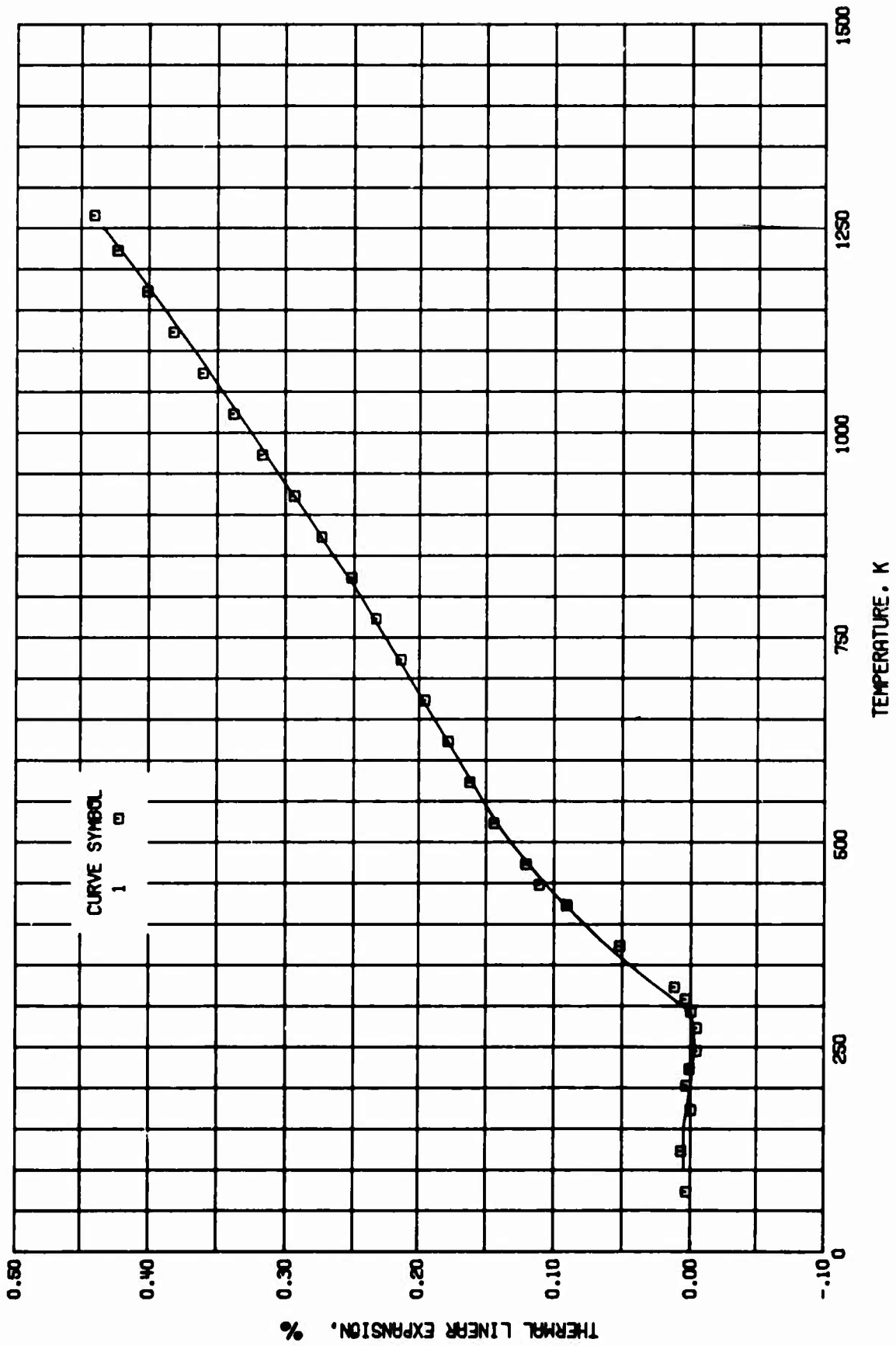


FIGURE 3-3. THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606) .

TABLE 3-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	86 Corning Glass Works	1958		73-1266		Hard, fine-grained crystalline material formed from special glasses; density 2.6 g cm ⁻³ .

TABLE 3-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 1			
73	0.003	723	0.214
123	0.007	773	0.233
173	0.000	823	0.252
203	0.003	873	0.274
223	0.001	923	0.294
245	-0.004	973	0.317
273	-0.004	1023	0.338
293	0.000	1073	0.361
308	0.004	1123	0.382
323	0.012	1173	0.401
373	0.052	1223	0.423
423	0.091	1266	0.440
448	0.111		
473	0.121		
523	0.144		
573	0.162		
623	0.178		
673	0.195		

e. Thermal Diffusivity

Seven sets of experimental data are available in the literature. The data are tabulated in Table 3-12 and shown partially in Figure 3-4. The information on specimen characterization and measurement condition for the data sets is given in Table 3-11.

The recommended values are calculated from the equation

$$\alpha = \frac{k}{C_p d}$$

using the recommended thermal conductivity, specific heat, and thermal linear expansion. The values agree to within $\pm 10\%$ with all the experimental data.

The recommended values are tabulated in Table 3-10 and shown in Figure 3-4. The uncertainty of the values is within $\pm 10\%$.

TABLE 3-10. RECOMMENDED THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

[Temperature, T, K; Thermal Diffusivity, α , $\text{cm}^2 \text{s}^{-1}$]

T	α
293	0.0194
300	0.0190
350	0.0170
400	0.0155
450	0.0143
500	0.0135
550	0.0128
600	0.0122
650	0.0117
700	0.0112
750	0.0108
800	0.0105
850	0.0102
900	0.0997
950	0.0975
1000	0.0955
1100	0.00921
1200	0.00893
1300	0.00872
1400	0.00858

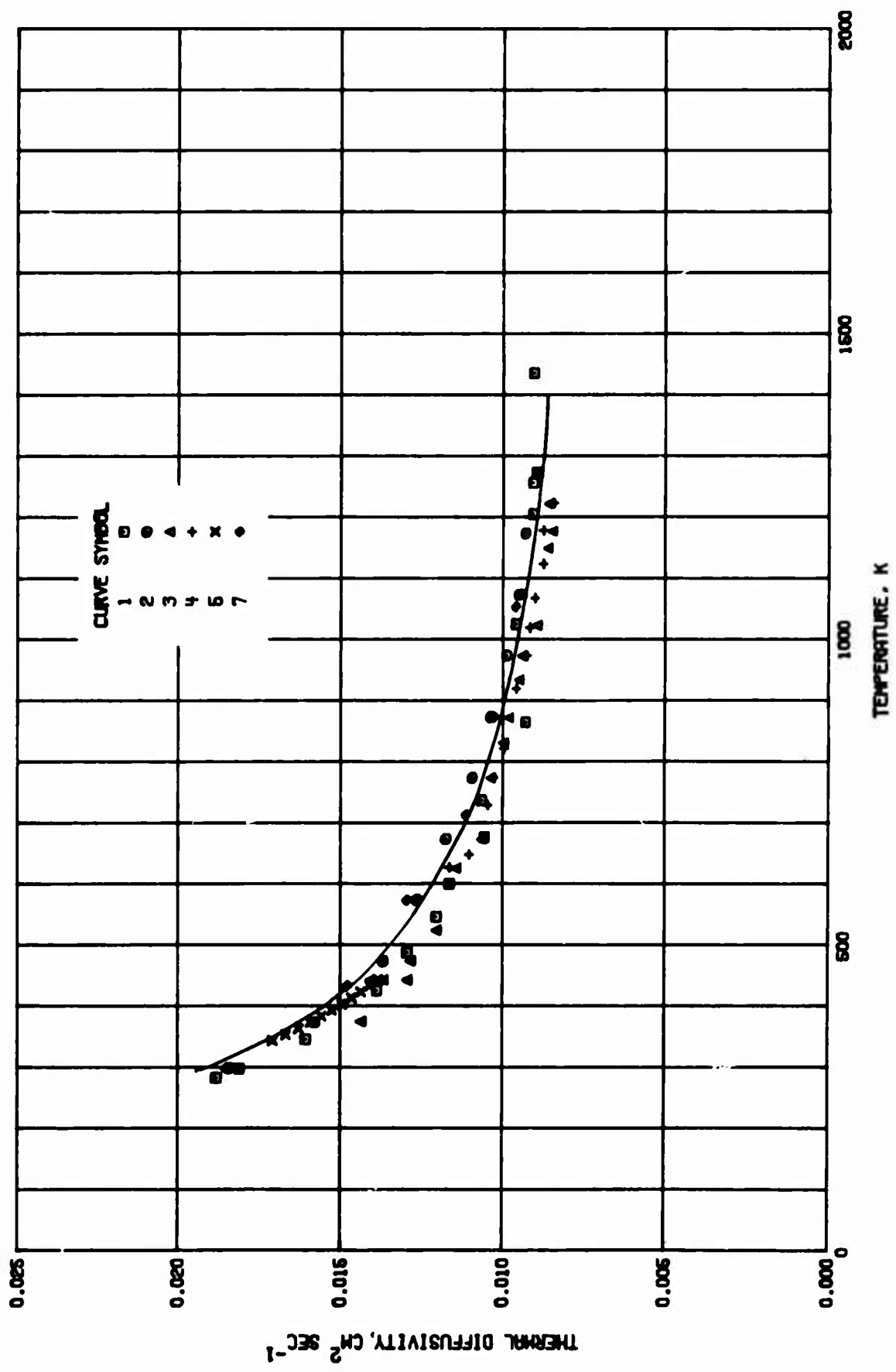


FIGURE 3-4. THERMAL DIFFUSIVITY OF PYROCERA (CORNING 9606).

TABLE 3-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 79, 87	Rudkin, R. L.	1963	T	283-1436		Glass-ceramic; disc specimen 0.75 in. in diameter and ~0.045 in. thick; developed at Corning Glass Works; coated on both sides with evaporated tungsten using electron beam techniques; short pulse of thermal energy from a xenon flash lamp absorbed at front surface of specimen; diffusivity determined from measured temperature-time function of the rear surface; measured in vacuum of $\sim 10^{-5}$ mm Hg; measurements below 873.2 K carried out in resistance furnace, measurements above 873.2 K made in vacuum induction furnace; reported error ± 5 to $\pm 10\%$.
2 88	Plummer, W. A., Campbell, D. E., and Comstock, A. A.	1962	T	98-1173		Specimen composed of three pieces: middle piece and two end pieces; middle piece separated from bottom piece by a 0.005 in. thick chromel sheet 7.6 x 18 cm forming the heat source, middle piece separated from upper piece by a 0.005 in. thick chromel sheet forming the heat sink; thicknesses on either side of the heater are the same; entire assembly constitutes a sandwich 12.7 cm long, 7.6 cm wide and at least 4 to 5 cm thick; diffusivity determined from measured ratio of the temperature rises of the heat source and sink; unidimensional heat flow; reported error $\sim 15\%$.
3 89	Gibby, R. L.	1968	T	375-1272		Cylindrical specimen 0.63 cm in diameter and 0.0544 cm thick; laser beam used as the pulse energy source; diffusivity determined from measured temperature history of the rear surface; both surfaces coated with colloidal graphite suspension; all data corrected for finite-pulse-time effects and heat losses; reported error $\pm 9\%$.
4 89	Gibby, R. L.	1968	T	626-1223		Same as the above specimen measured for diffusivity during cooling; other conditions same as above.
5 90	Flieger, H. W., Jr.	1963		343-973		Microcrystalline specimen, 2 in. in diameter and 14 in. long; diffusivity measured in series 1.
6* 90	Flieger, H. W., Jr.	1963		343-1273		Same as the above specimen; diffusivity measured in series 2.
7 91	Plummer, W. A.	1963		298-1053		Specimen 12.7 cm by 7.6 cm.

* Not shown in figure.

TABLE 3-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF PYROCERAM (CORNING 9606)

T	α	T	α	T	α	T	α	T	α	T	α
CURVE 1				CURVE 3 (cont.)				CURVE 5 (cont.)			
283	0.0186	1023	0.00692	573	0.01225	373	0.01587	843	0.00994	298	0.0185
296	0.0181	1075	0.00939	583	0.01214	383	0.01554	853	0.00989	433	0.0148
346	0.0181	1149	0.00658	593	0.01203	393	0.01522	863	0.00984	573	0.0130
426	0.0139	1177	0.00644	603	0.01192	403	0.01492	873	0.00979	713	0.0112
468	0.0130	1222	0.00656	613	0.01182	413	0.01464	883	0.00974	873	0.0103
546	0.0121	1272	0.00689	623	0.01172	423	0.01437	893	0.00969	1053	0.0096
600	0.0117			633	0.01163	433	0.01411	903	0.00964		
CURVE 4											
676	0.0106			643	0.01153	443	0.01386	913	0.00959		
737	0.0107			653	0.01144	453	0.01381	923	0.00955		
795	0.0100	626	0.0117	663	0.01136	463	0.01361	933	0.00950		
865	0.00930	647	0.0111	673	0.01127	473	0.01342	943	0.00946		
1025	0.00960	728	0.0105	683	0.01119	483	0.01325	953	0.00942		
1205	0.00905	773	0.0103	693	0.01111	493	0.01308	963	0.00937		
1256	0.00905	821	0.00998	703	0.01104	503	0.01292	973	0.00933		
1273	0.00995	919	0.00958	713	0.01096	513	0.01277	983	0.00929		
1436	0.00903	973	0.00924	723	0.01089	523	0.01263	993	0.00925		
		1019	0.00916	733	0.01082	533	0.01249	1003	0.00921		
CURVE 2											
296	0.0184	1067	0.00698	743	0.01075	543	0.01236	1013	0.00917		
373	0.0137	1123	0.00672	753	0.01069	553	0.01223	1023	0.00913		
473	0.0127	1178	0.00672	763	0.01062	563	0.01211	1033	0.00910		
573	0.0118	1223	0.00640	773	0.01056	573	0.01200	1043	0.00906		
673	0.0118			783	0.01050	583	0.01189	1053	0.00902		
773	0.0110			793	0.01044	593	0.01178	1063	0.00899		
873	0.0104			803	0.01039	603	0.01168	1073	0.00895		
973	0.0099	343	0.01709	813	0.01033	613	0.01158	1083	0.00892		
1073	0.0095	353	0.01669	823	0.01028	623	0.01148	1093	0.00888		
1173	0.0093	363	0.01630	833	0.01023	633	0.01139	1103	0.00885		
		373	0.01594	843	0.01018	643	0.01130	1113	0.00882		
		383	0.01560	853	0.01013	653	0.01121	1123	0.00878		
CURVE 3											
375	0.0144	393	0.01527	863	0.01008	663	0.01113	1133	0.00875		
443	0.0137	403	0.01496	873	0.01004	673	0.01105	1143	0.00872		
443	0.0137	413	0.01467	883	0.00999	683	0.01097	1153	0.00869		
443	0.0141	423	0.01439	893	0.00995	693	0.01089	1163	0.00866		
443	0.0130	433	0.01412	903	0.00991	703	0.01082	1173	0.00863		
474	0.0124	443	0.01386	913	0.00986	713	0.01074	1183	0.00860		
476	0.0124	453	0.01391	923	0.00982	723	0.01067	1193	0.00857		
476	0.0123	463	0.01375	933	0.00978	733	0.01060	1203	0.00854		
524	0.0121	473	0.01359	943	0.00975	743	0.01053	1213	0.00851		
581	0.0122	483	0.01344	953	0.00971	753	0.01047	1223	0.00848		
625	0.0115	493	0.01329	963	0.00967	763	0.01040	1233	0.00846		
673	0.0107	503	0.01315	973	0.00964	773	0.01034	1243	0.00843		
773	0.0104	513	0.01301			783	0.01028	1253	0.00840		
831	0.0100	523	0.01287			793	0.01022	1263	0.00837		
872	0.00983	533	0.01274			803	0.01016	1273	0.00835		
934	0.00950	543	0.01261			813	0.01011				
973	0.00941	553	0.01249			823	0.01005				
		563	0.01237			833	0.00999				
CURVE 6*											
		343	0.01653								
		353	0.01659								
		363	0.01622								

*** Not shown in figure.**

3.4. Silicon Nitride (Si_3N_4)

Bulk silicon nitride is manufactured by reacting silicon powder with nitrogen at elevated temperatures (above 1573 K). It is used as a hard refractory material in high-temperature ceramic applications with a useful service temperature of about 1500 K. It dissociates at about 2200 K. It has been reported [92] that there are two types of crystal structure of silicon nitride, $\alpha\text{-Si}_3\text{N}_4$ and $\beta\text{-Si}_3\text{N}_4$, both of which are hexagonal but with different lattice constants in the c-axis. It has also been reported [93] that silicon nitride has four types of crystal structure. Silicon nitride is a good electrical insulator with reported electrical resistivity of $10^{12} \Omega \text{ cm}$ at room temperature and $10^6 \Omega \text{ cm}$ at 1300 K. It has a very low coefficient of thermal expansion; as a result, its thermal shock resistance is very good so that it can be used as a high-temperature radome material. Its theoretical room-temperature density is 3.16 g cm^{-3} [95].

Dense silicon nitride is produced by hot pressing and sintering silicon powder compact in a nitrogen atmosphere at high pressure and at a temperature near the melting point of silicon (1687 K). Using this technique, laboratory preparations have resulted in samples of 98% purity.

There is considerable increase of interest in silicon nitride thin films for micro-electronic applications in the recent years. Silicon nitride films can be prepared by several different deposition techniques: direct nitridation, evaporation, glow discharge (dc and rf), sputtering (dc, rf, and reactive), and pyrolysis (chemical vapor deposition). The reactive sputtering and pyrolysis methods have been most frequently utilized. In each of these deposition methods, several parameters can be varied: temperature, flow rate, plasma density, pressure or degree of vacuum, ratio of reactants, and electric field. Prior to deposition, the substrates are usually given a mechanical lap followed by a mechanical or chemical polish. Heat treatment of the film is also utilized.

a. Thermal Conductivity

There are 36 sets of data available for the thermal conductivity of silicon nitride. Most of the measurements are on porous specimens with density ranging from approximately 2.0 g cm^{-3} to 2.8 g cm^{-3} , and only two sets (curves 3 and 24) are on nearly non-porous specimens (density $\approx 3.1 \text{ g cm}^{-3}$). The experimental data are tabulated in Table 4-3 and shown partially in Figure 4-1. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-2. The existing evidence seems to indicate that the thermal conductivity of silicon nitride depends not only on porosity and purity, but also on the relative abundance of the α and the β phases

and on the method of fabrication [95, 96]. For these reasons, only provisional values are given for the thermal conductivity. The values for a porous polycrystalline specimen of density 2.4 g cm^{-3} (approximate porosity 75%) are based on the data of Wells [96] at higher temperatures and of Godfrey and Lindley [95] at room temperature. The uncertainty of the provisional values is about $\pm 20\%$.

The thermal conductivity values for non-porous polycrystalline silicon nitride are estimated from those for the porous silicon nitride using the expression given by Koh and Fortini [156]:

$$\frac{k}{k_o} = \frac{1 - P}{1 + 11P^2}$$

where k and k_o are the thermal conductivities of the porous and the non-porous materials, respectively, and P is the porosity. The resulting values agree quite well with the data of Powell and Tye [94] (Curve 24) over the temperature range of their measurement, both in temperature dependence and in magnitude. Their uncertainty is estimated to be about $\pm 15\%$ below 400 K and $\pm 25\%$ at higher temperatures.

TABLE 4-1. PROVISIONAL THERMAL CONDUCTIVITY OF SILICON NITRIDE (Si_3N_4)[Temperature, T, K; Thermal Conductivity, k, $\text{W cm}^{-1} \text{K}^{-1}$]

T	k	
	Density 2.4 g cm^{-3}	Density 3.16 g cm^{-3}
273.15	0.167	0.360
293	0.162	0.349
300	0.160	0.343
350	0.148	0.319
400	0.139	0.299
450	0.131	0.282
500	0.125	0.268
550	0.118	0.254
600	0.113	0.243
650	0.109	0.235
700	0.105	0.226
750	0.101	0.218
800	0.0988	0.213
850	0.0951	0.205
900	0.0924	0.199
950	0.0899	0.194
1000	0.0876	0.189
1100	0.0836	0.180
1200	0.0800	0.172
1300	0.0769	0.166
1400	0.0741	0.160
1500	0.0716	0.154
1600	0.0693	0.149
1700	0.0672	0.145
1800	0.0653	0.141
1900	0.0636	0.137
2000	0.0620	0.134

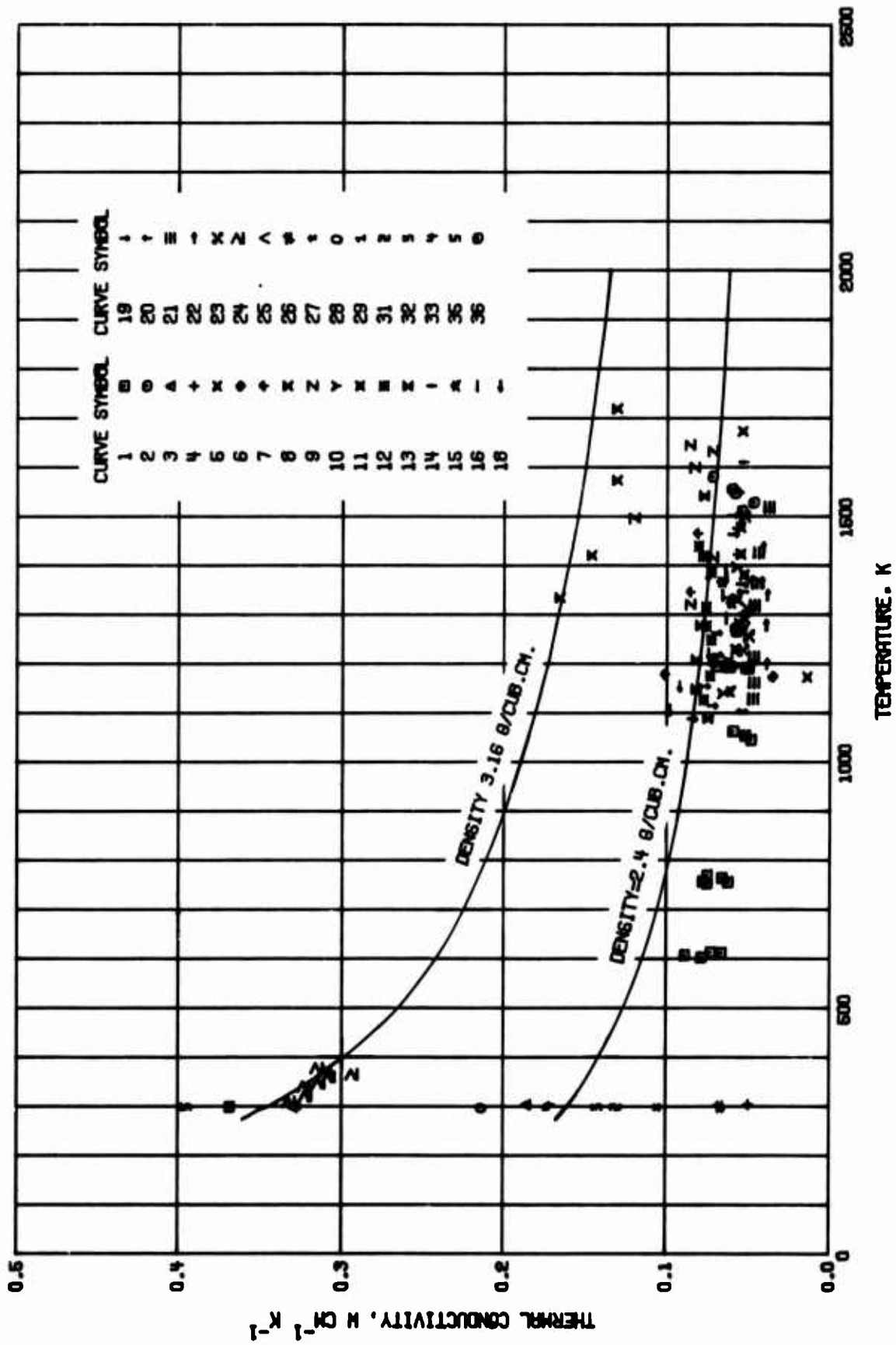


FIGURE 4-1. THERMAL CONDUCTIVITY OF POLYCRYSTALLINE SILICON NITRIDE.

TABLE 4-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF SILICON NITRIDE Si_3N_4

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 61, 98	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962	R	603-1195		Impurities 0.05 Ca, 0.01 Cu, 0.01 Mg, 0.3 Al, 1.5 Fe, 0.01 Ti, and trace Be, Na, and Mn; cast; specimen 3/4 in. O.D. 1/4 in. I.D. 3/4 in. long; density 2.38 g cm^{-3} ; reported error 2.5%.
2 61, 98	Neel, D.S., et al.	1962	R	1267-2061		Second run of the above specimen; melted during run.
3 99, 100	Powell, R.W. and Tye, R.P.	1962	C	303		Density 3.16 g cm^{-3} ; data read from calibration of a direct-reading thermal comparator.
4 99, 100	Powell, R.W. and Tye, R.P.	1962	C	303		Data for specimen of density 2.34 g cm^{-3} .
5 101	Swartz, E.L. and Crandall, W.B.	1955	P	1173, 1673		Porosity 70%; thermal conductivity calculated from measured thermal diffusivity, density, and specific heat.
6 101	Swartz, E.L. and Crandall, W.B.	1955	P	1173.2		Similar to the above specimen but porosity 85%.
7 96	Wells, W.M.	1964	R	1178-1465	RD	1.25 in. O.D. x 0.25 in. I.D. x 1.25 in. long; density 2.33 g cm^{-3} .
8 96	Wells, W.M.	1964	R	1334-1719	LRL	Similar to the above specimen but density 2.5 g cm^{-3} .
9 96	Wells, W.M.	1964	R	1320-1644	EC	Similar to the above specimen but density 2.1 g cm^{-3} .
10 96	Wells, W.M.	1964	R	1139-1396	H-3-TS	Similar to the above specimen but density 2.21 g cm^{-3} .
11 96	Wells, W.M.	1964	R	1204-1477	H-2-TS	Similar to the above specimen but density 2.32 g cm^{-3} .
12 96	Wells, W.M.	1964	R	1126-1439	EC-1-TS	Similar to the above specimen.
13 96	Wells, W.M.	1964	R	1088-1542	EC-3-TS	Similar to the above specimen.
14 96	Wells, W.M.	1964	R	1178-1610	EC-7-TS	Similar to the above specimen but density 2.22 g cm^{-3} .
15 96	Wells, W.M.	1964	R	1143-1366	EC-2-TS	Similar to the above specimen but density 2.34 g cm^{-3} .
16 96	Wells, W.M.	1964	R	1186-1391	N-10-TS	Similar to the above specimen but density 2.38 g cm^{-3} .
17* 96	Wells, W.M.	1964	R	1180-1384	N-1-TS	Similar to the above specimen.
18 96	Wells, W.M.	1964	R	1106-1436	N-5-TS	Similar to the above specimen but density 2.33 g cm^{-3} .
19 96	Wells, W.M.	1964	R	1087-1501	N-6-TS	Similar to the above specimen but density 2.32 g cm^{-3} .
20 96	Wells, W.M.	1964	R	1103-1471	CS-1-TS	Similar to the above specimen but density 2.01 g cm^{-3} .
21 96	Wells, W.M.	1964	R	1128-1519	CS-2-TS	Similar to the above specimen but density 2.15 g cm^{-3} .
22 96	Wells, W.M.	1964	R	1199-1436	CS-3-TS	Similar to the above specimen but density 2.07 g cm^{-3} .
23 96	Wells, W.M.	1964	R	1143-1499	CS-4-TS	Similar to the above specimen but density 2.17 g cm^{-3} .
24 94	Powell, R.W. and Tye, R.P.	1969	C	309-377		High purity; specimen square section area 0.000091 m^2 ; supplied by Messrs. Plessey, U.K. Ltd.; density 3.1 g cm^{-3} .
25 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1471	Flame sprayed; density 2.84 g cm^{-3} ; thermal conductivity value calculated from measured thermal diffusivity using the literature data of specific heat.
26 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1473	Density 1.99 g cm^{-3} .

* Not shown in figure.

TABLE 4-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF SILICON NITRIDE Si_3N_4 (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Specimen Designation	Composition (weight percent), Specifications, and Remarks
27 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1474	Density 2.00 g cm ⁻³ .
28 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1475	Density 2.34 g cm ⁻³ .
29 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1478	Density 2.43 g cm ⁻³ .
30* 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AML 1482	Density 2.63 g cm ⁻³ .
31 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	AME	Density 2.52 g cm ⁻³ .
32 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	BSA	Density 2.47 g cm ⁻³ .
33 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	Lucas	Flame sprayed; density 2.59 g cm ⁻³ .
34* 95	Godfrey, D.J. and Lindley, M.W.	1972	P	298	Lucas	Hot-pressed; density 3.07 g cm ⁻³ .
35 102	Lange, F.F.	1972	L	298		0.5 x 0.25 x 0.25 in.; hot-pressed; heat flow perpendicular to pressing direction; reported error 2%.
36 102	Lange, F.F.	1972	L	298		Similar to the above specimen but heat flow parallel to pressing direction.

* Not shown in figure.

T	k	T	k	T	k	T	k	T	k	T	k	T	k	T	k	T	k				
<u>CURVE 1</u>				<u>CURVE 6</u>				<u>CURVE 12 (cont.)</u>				<u>CURVE 17*</u>				<u>CURVE 22</u>					
603.2	0.0786	1173.2	0.00360	1248	0.0730	1180	0.101	1199	0.0394	298	0.328	1199	0.0394	298	0.328	1199	0.0394				
607.1	0.0687	<u>CURVE 7</u>		1276	0.0763	1268	0.0763	1278	0.0401	1378	0.0401	1278	0.0401	1378	0.0401	1278	0.0401				
611.5	0.0663	1178	0.101	1314	0.0763	1314	0.0763	1332	0.0392	1339	0.0392	1339	0.0392	1339	0.0392	1339	0.0392				
613.2	0.0727	1346	0.0857	1366	0.0731	1366	0.0731	1384	0.0425	1436	0.0425	1384	0.0425	1436	0.0425	1384	0.0425				
753.2	0.0750	1465	0.0812	1418	0.0785	1418	0.0785	<u>CURVE 18</u>				1436	0.0417	298	0.214	298	0.214				
755.4	0.0623	<u>CURVE 8</u>		1439	0.0808	<u>CURVE 13</u>		<u>CURVE 19</u>				<u>CURVE 31</u>				<u>CURVE 33</u>					
757.1	0.0779	1320	0.0861	1542	0.0776	1106	0.0982	1067	0.0847	1187	0.0847	1106	0.0982	1067	0.0847	1187	0.0847				
763.7	0.0779	1416	0.0721	<u>CURVE 14</u>		1154	0.0924	1114	0.0721	1114	0.0721	1154	0.0924	1114	0.0721	1114	0.0721				
764.3	0.0661	1496	0.120	1178	0.0610	1219	0.0692	1219	0.0692	1219	0.0692	1219	0.0692	1219	0.0692	1219	0.0692				
769.3	0.0750	1599	0.0835	1216	0.0711	1263	0.0697	1263	0.0697	1263	0.0697	1263	0.0697	1263	0.0697	1263	0.0697				
1045.4	0.0490	1632	0.0724	1362	0.0554	1301	0.0643	1301	0.0643	1301	0.0643	1301	0.0643	1301	0.0643	1301	0.0643				
1054.3	0.0525	1644	0.0665	1421	0.0573	1334	0.0630	1334	0.0630	1334	0.0630	1334	0.0630	1334	0.0630	1334	0.0630				
1063.2	0.0596	<u>CURVE 9</u>		1475	0.0577	1408	0.0561	1408	0.0561	1408	0.0561	1408	0.0561	1408	0.0561	1408	0.0561				
1064.3	0.0594	1139	0.0662	1511	0.0555	1463	0.0599	1463	0.0599	1463	0.0599	1463	0.0599	1463	0.0599	1463	0.0599				
1190.4	0.0503	1281	0.0564	1548	0.0564	1501	0.0601	1501	0.0601	1501	0.0601	1501	0.0601	1501	0.0601	1501	0.0601				
1192.6	0.0522	1396	0.0590	1610	0.0539	<u>CURVE 15</u>		<u>CURVE 20</u>				377.2	0.313	298	0.368	298	0.368				
1193.7	0.0617	<u>CURVE 10</u>		<u>CURVE 16</u>		1143	0.0619	1103	0.0544	1103	0.0544	1103	0.0544	1103	0.0544	1103	0.0544				
1194.8	0.0696	1204	0.0627	1186	0.0626	1194	0.0637	1196	0.0558	1196	0.0558	1196	0.0558	1196	0.0558	1196	0.0558				
<u>CURVE 2</u>				1229	0.0584	1234	0.0593	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570				
1266.5	0.0575	1261	0.0560	1266	0.0548	1266	0.0548	1346	0.0542	1346	0.0542	1346	0.0542	1346	0.0542	1346	0.0542				
1272.1	0.0584	1291	0.0587	1323	0.0613	1366	0.0669	1386	0.0554	1386	0.0554	1386	0.0554	1386	0.0554	1386	0.0554				
1294.3	0.0591	1332	0.0577	1366	0.0669	<u>CURVE 21</u>		1471	0.0577	1471	0.0577	1471	0.0577	1471	0.0577	1471	0.0577				
1311.0	0.0548	1396	0.0590	<u>CURVE 11</u>		<u>CURVE 16</u>				<u>CURVE 27</u>				<u>CURVE 28</u>							
1327.6	0.0476	1139	0.0662	1186	0.0626	1194	0.0637	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570				
1347.1	0.0594	1204	0.0627	1229	0.0584	1234	0.0593	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548				
1355.4	0.0606	1261	0.0560	1291	0.0587	1323	0.0613	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669				
1380.6	0.0721	1332	0.0577	1396	0.0590	1477	0.0555	<u>CURVE 21</u>				298	0.067	298	0.067	298	0.067				
2044.3	0.0715	1381	0.0534	1423	0.0555	<u>CURVE 12</u>		<u>CURVE 16</u>				<u>CURVE 27</u>				<u>CURVE 28</u>					
2047.1	0.0600	1477	0.0555	1186	0.0626	1194	0.0637	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570				
2061.0	0.0734	1204	0.0627	1229	0.0584	1234	0.0593	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548				
<u>CURVE 3</u>				1291	0.0587	1323	0.0613	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669				
303	0.185	1332	0.0577	1396	0.0594	1477	0.0555	<u>CURVE 21</u>				298	0.067	298	0.067	298	0.067				
<u>CURVE 4</u>				1423	0.0555	<u>CURVE 12</u>		<u>CURVE 16</u>				<u>CURVE 27</u>				<u>CURVE 28</u>					
303	0.050	1477	0.0555	1186	0.0626	1194	0.0637	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570				
<u>CURVE 5</u>				1229	0.0584	1234	0.0593	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548				
1173.2	0.0146	1291	0.0587	1323	0.0613	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669	1366	0.0669				
1673.2	0.0544	1396	0.0590	1477	0.0555	<u>CURVE 12</u>				<u>CURVE 16</u>				<u>CURVE 27</u>				<u>CURVE 28</u>			
1173.2	0.0146	1477	0.0555	1186	0.0626	1194	0.0637	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570	1289	0.0570				
1673.2	0.0544	1204	0.0627	1229	0.0584	1234	0.0593	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548	1266	0.0548				

**** Not shown in figure.**

b. Specific Heat

There are six sets of experimental data available for the specific heat of silicon nitride. The information on the specimen characterization and measurement conditions for each data set is given in Table 4-5. The experimental data are tabulated in Table 4-6 and shown in Figure 4-2.

These experimental data sets cover the temperature range 273-2200 K. The recommended values shown in Figure 4-2 and tabulated in Table 4-4 are derived primarily from the measurements of Kelley [103] (curve 2), Satoh [104] (curve 4), and McLean, Fisher, and Bratton [105] (curve 6). The specific heat data of Neel, Pears, and Oglesby [61] (curve 3) are about 7-15% higher than the recommended values above 1400 K. The mixing rule calculations of Pehlke and Elliott [106] (curve 1) yield values which are up to 35% higher below 800 K and 15% lower above that temperature. The uncertainty of the recommended values is $\pm 5\%$ below 1000 K and $\pm 10\%$ above that temperature.

TABLE 4-4. RECOMMENDED SPECIFIC HEAT OF
SILICON NITRIDE (Si_3N_4)

[Temperature, T, K; Specific Heat, C_p , $\text{cal g}^{-1} \text{K}^{-1}$]

T	C_p
200	0.138
250	0.152
273.15	0.158
293	0.163
300	0.165
350	0.176
400	0.186
450	0.197
500	0.206
550	0.215
600	0.224
650	0.233
700	0.242
750	0.248
800	0.254
850	0.260
900	0.266
950	0.271
1000	0.276
1100	0.285
1200	0.293
1300	0.301
1400	0.307
1500	0.312
1600	0.316
1700	0.320
1800	0.324
1900	0.327
2000	0.329

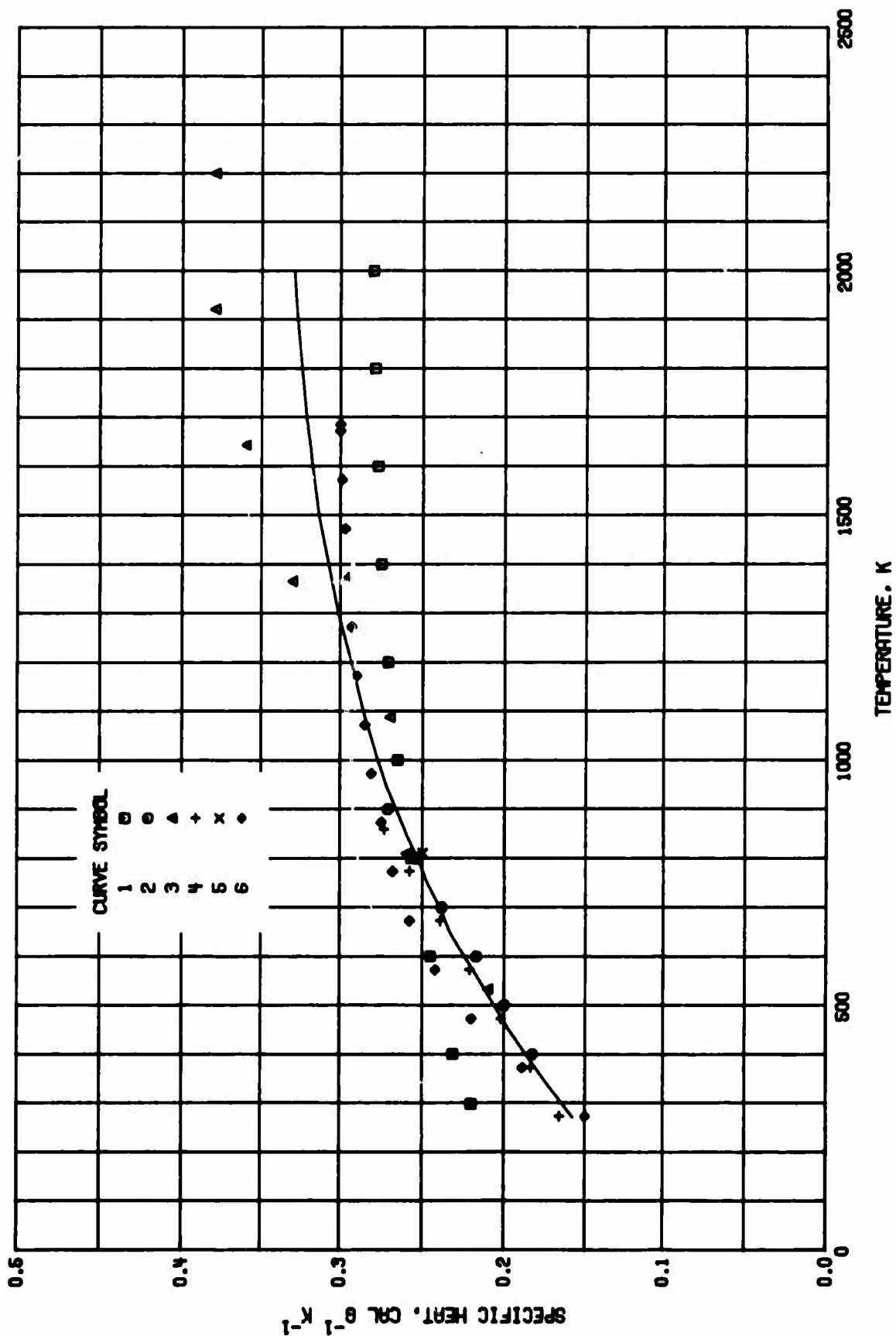


FIGURE 4-2. SPECIFIC HEAT OF SILICON NITRIDE .

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 106	Pehlke, R. D. and Elliott, J. F.	1959		298-2000		Values calculated from $C_p(\text{Si}_3\text{N}_4) = 2.5 + 3C_p^0(\text{Si}) + 2C_p^0(\text{N}_2)$ cal deg ⁻¹ mole ⁻¹ ; molecular weight 140.286 was assumed.
2 103	Kelley, K. K.	1949		400-900		NBS compilation, $C_p = 16.83 + 23.6 \times 10^{-4} T$ cal deg ⁻¹ mole ⁻¹ ; molecular weight 140.286 was assumed.
3 61	Neel, D. S., Pears, C. D., and Oglesby, S., Jr.	1962		533-2200		98.12 Si ₃ N ₄ , 1.5 Fe, 0.3 Al, 0.05 Ca, 0.01 each Cu, Mg, Ti, and traces of Ba, Mn, and Na; supplied by the Carborundum Co.; density 2.37 g cm ⁻³ ; C_p values calculated from the heat content measurements.
4 104	Satch, S.	1938		273-858		Specimen prepared by reacting SiCl ₄ with NH ₃ to form Si(NH ₂) ₄ which was heated stepwise to 1473 K to obtain the final product; values calculated from the equation $C_p = 0.1656 + 1.847 \times 10^{-4} t - 4.5 \times 10^{-7} t^2$ (t in °C).
5 107	Washburn, M. E.	1967		810		No details given.
6 105	McLean, A. F., Fisher, E. A., and Bratton, R. J.	1973	1	273-1673		Reaction sintered; injection molded specimen having nitrided density 2.23 g cm ⁻³ .

TABLE 4-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF SILICON NITRIDE Si_3N_4

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹][illegible]

c. Heat of Fusion

Silicon nitride decomposes at 2200 K. The standard heat of formation, ΔH_{298}° , of silicon nitride for the reaction in which decomposition pressure of nitrogen reaches one atmosphere is $1270 \pm 50 \text{ cal g}^{-1}$ according to Stull and Prophet [108].

d. Thermal Linear Expansion

Silicon nitride occurs in two crystalline forms having nearly the same densities and crystallographic structures (c. p. h.). α - Si_3N_4 is formed at lower temperature and β - Si_3N_4 at higher (≈ 1800 K) temperature. β - Si_3N_4 can be obtained by an irreversible reaction by heating α - Si_3N_4 at high temperature in the presence of nitrogen. The temperature at which the nitride is formed is an important factor in determining the phase. The thermal expansion data for each of the two forms of Si_3N_4 are treated separately.

There are 33 sets of experimental data available for the thermal linear expansion of Si_3N_4 . The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-8. The experimental data are tabulated in Table 4-9 and partially shown in Figures 4-3A thru 4-3E. The temperature range covered by these data sets is 273-2100 K.

α - Si_3N_4

There are 4 sets of experimental data (curves 18, 20, 22, and 24) for measurements parallel to a-axis. These are shown in Figure 4-3A. There are 4 sets of experimental data (curves 19, 21, 23, and 25) for measurements parallel to c-axis. These are shown in Figure 4-3B. The experimental data for polycrystalline material (curves 1-15) are partially shown in Figure 4-3C. For an anisotropic material like Si_3N_4 , it is customary to select the most probable values for thermal linear expansion parallel to and perpendicular to the c-axis, and from these to calculate the values for a randomly oriented polycrystalline material. However, this procedure can not be applied here due to the lack of reliable data for the single crystal.

The provisional values for polycrystalline α - Si_3N_4 shown in Figure 4-3C and tabulated in Table 4-7A are derived primarily from the measurements of Tokuyama et al. [109] (curve 1), Burkhardt and Marvel [110] (curve 14), Gregor [111] (curve 15), Steel et al. [112] (curve 2), and of Wells [96] (curves 3-6). The data reported by Neel et al. [61] (curves 8-12) are inconsistent; moreover, they seemed to have problem with their specimen (curve 13). The uncertainty of the provisional values is about $\pm 15\%$.

The values of the instantaneous coefficient of thermal linear expansion, α , are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about $\pm 20\%$.

The provisional values for directions parallel to the a-axis (perpendicular to the c-axis) and parallel to the c-axis reported in Table 4-7A and shown in Figures 4-3A and 4-3B are based on the provisional values for polycrystalline material and on the trends of the data reported by Thompson and Pratt [113] (curves 18 and 19) and by Iwai and Yasunaga [114] (curves 24 and 25).

The specimens used by Thompson and Pratt [113] (curves 20-23) seemed to have been contaminated by free silicon and oxygen giving anomolous results around 700-1150 K. Their results above 1150 K are too low. The data of Iwai and Yasunaga [114] are also too low. The uncertainty of the provisional values is about $\pm 15\%$.

β - Si_3N_4

No experimental data for the thermal linear expansion for polycrystalline β - Si_3N_4 were located in the literature. The provisional values reported in Table 4-7B and shown in Figures 4-3D and 4-3E are based on the data of Thompson and Pratt [113] (curves 16 and 17) and of Iwai and Yasunaga [114] (curves 26 and 27). The phase formed at higher temperature generally has lower thermal expansion values than the phase formed at lower temperature. In generating the provisional values for the a-axis (perpendicular to the c-axis) and the c-axis, the shape of the thermal linear expansion curves for α - Si_3N_4 were also taken into account.

The provisional values for polycrystalline β - Si_3N_4 tabulated in Table 4-7B and shown in Figure 4-3C were calculated from the provisional values for a-axis and c-axis. These values are considered accurate to within $\pm 15\%$. The values of the instantaneous coefficient of thermal linear expansion, α , are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion data, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty in these values is about $\pm 15\%$.

TABLE 4-7A. PROVISIONAL THERMAL LINEAR EXPANSION OF ALPHA SILICON NITRIDE (α -Si₃N₄)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	\perp c-axis	// c-axis	Polycrystalline	
	$\Delta L/L_0$	$\Delta L/L_0$	$\Delta L/L_0$	α
293	0.000	0.000	0.000	1.2
310	0.0003	0.002	0.001	1.4
320	0.001	0.003	0.002	1.4
340	0.004	0.008	0.005	1.6
350	0.005	0.010	0.007	1.6
360	0.006	0.012	0.008	1.7
380	0.007	0.016	0.010	1.8
400	0.010	0.020	0.013	1.9
420	0.014	0.026	0.018	2.0
450	0.020	0.035	0.025	2.2
500	0.029	0.051	0.036	2.4
550	0.041	0.066	0.049	2.6
600	0.054	0.080	0.063	2.8
650	0.069	0.096	0.078	3.0
700	0.083	0.112	0.093	3.1
750	0.098	0.129	0.108	3.2
800	0.114	0.145	0.124	3.3
850	0.130	0.163	0.141	3.3
900	0.147	0.179	0.158	3.4
950	0.163	0.197	0.174	3.4
1000	0.180	0.215	0.192	3.5
1100	0.213	0.253	0.226	3.5
1200	0.249	0.290	0.263	3.6
1300	0.285	0.329	0.300	3.7
1400	0.322	0.367	0.337	3.8
1500	0.360	0.405	0.375	3.9
1600	0.400	0.443	0.414	3.9
1700	0.440	0.482	0.454	4.0
1800	0.480	0.520	0.493	4.0
1900	0.520	0.558	0.533	4.1
2000	0.560	0.596	0.572	4.1

TABLE 4-7B. PROVISIONAL THERMAL LINEAR EXPANSION OF BETA
SILICON NITRIDE (β -Si₃N₄)

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	\perp c-axis	// c-axis	Polycrystalline	
	$\Delta L/L_0$	$\Delta L/L_0$	$\Delta L/L_0$	α
293	0.000	0.000	0.000	1.0
310	0.001	0.002	0.001	1.2
320	0.001	0.003	0.002	1.2
340	0.002	0.006	0.003	1.4
350	0.002	0.007	0.004	1.4
360	0.003	0.009	0.005	1.5
380	0.005	0.011	0.007	1.6
400	0.009	0.013	0.010	1.7
420	0.010	0.016	0.012	1.9
450	0.019	0.022	0.020	2.0
500	0.032	0.032	0.032	2.3
550	0.044	0.045	0.044	2.5
600	0.057	0.058	0.057	2.7
650	0.071	0.073	0.072	2.8
700	0.086	0.088	0.087	3.0
750	0.100	0.105	0.102	3.1
800	0.114	0.122	0.117	3.2
850	0.129	0.140	0.133	3.3
900	0.144	0.159	0.149	3.3
950	0.159	0.179	0.166	3.4
1000	0.174	0.198	0.182	3.4
1100	0.205	0.239	0.216	3.5
1200	0.237	0.282	0.252	3.6
1300	0.271	0.325	0.289	3.6
1400	0.303	0.369	0.325	3.7
1500	0.337	0.414	0.362	3.7
1600	0.370	0.461	0.399	3.8
1700	0.404	0.507	0.438	3.9
1800	0.438	0.554	0.477	3.9
1900	0.474	0.601	0.516	4.0
2000	0.511	0.649	0.557	4.0

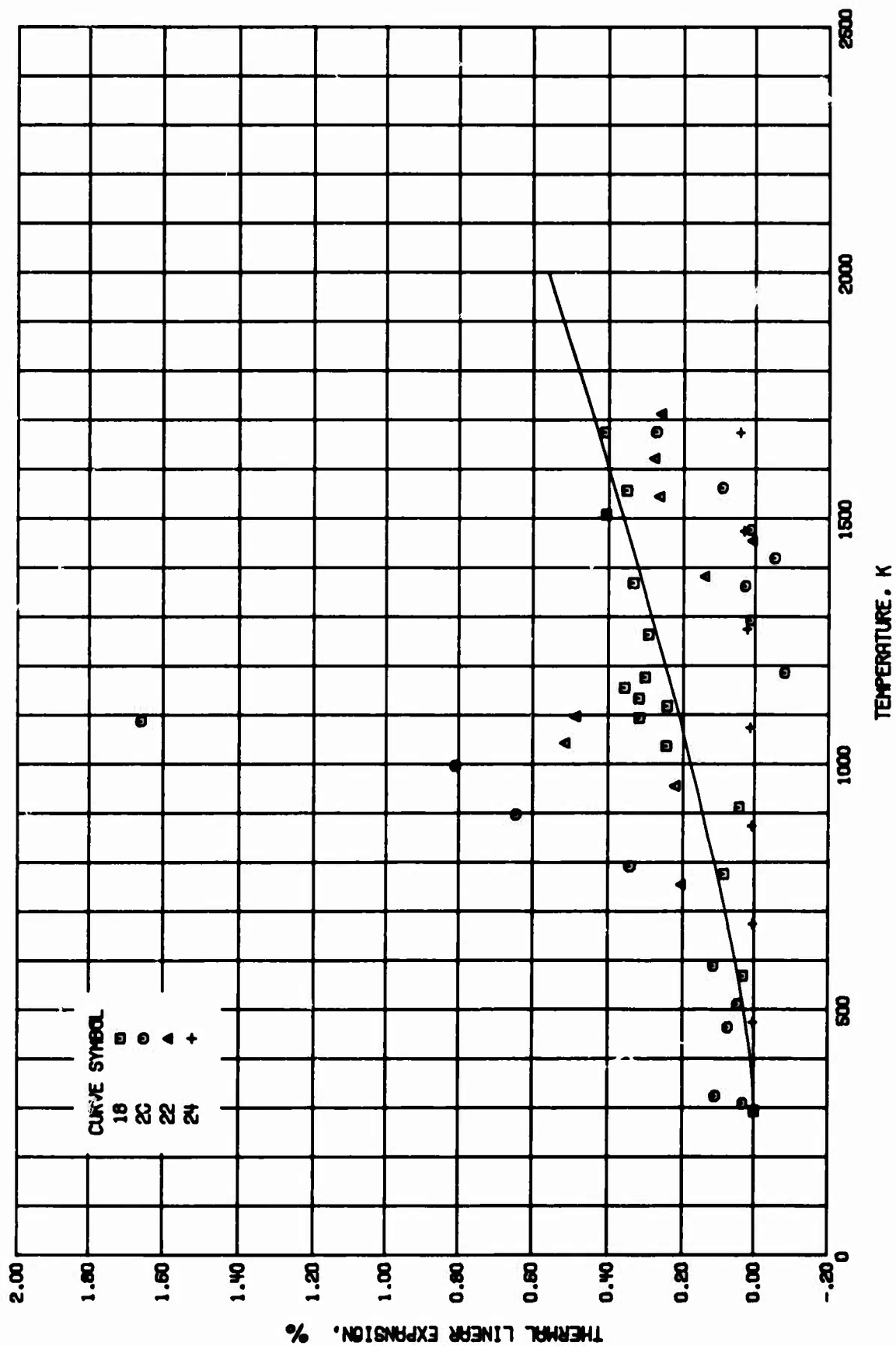


FIGURE 4-3A. THERMAL LINEAR EXPANSION OF ALPHA-SILICON NITRIDE PARALLEL TO A-AXIS .

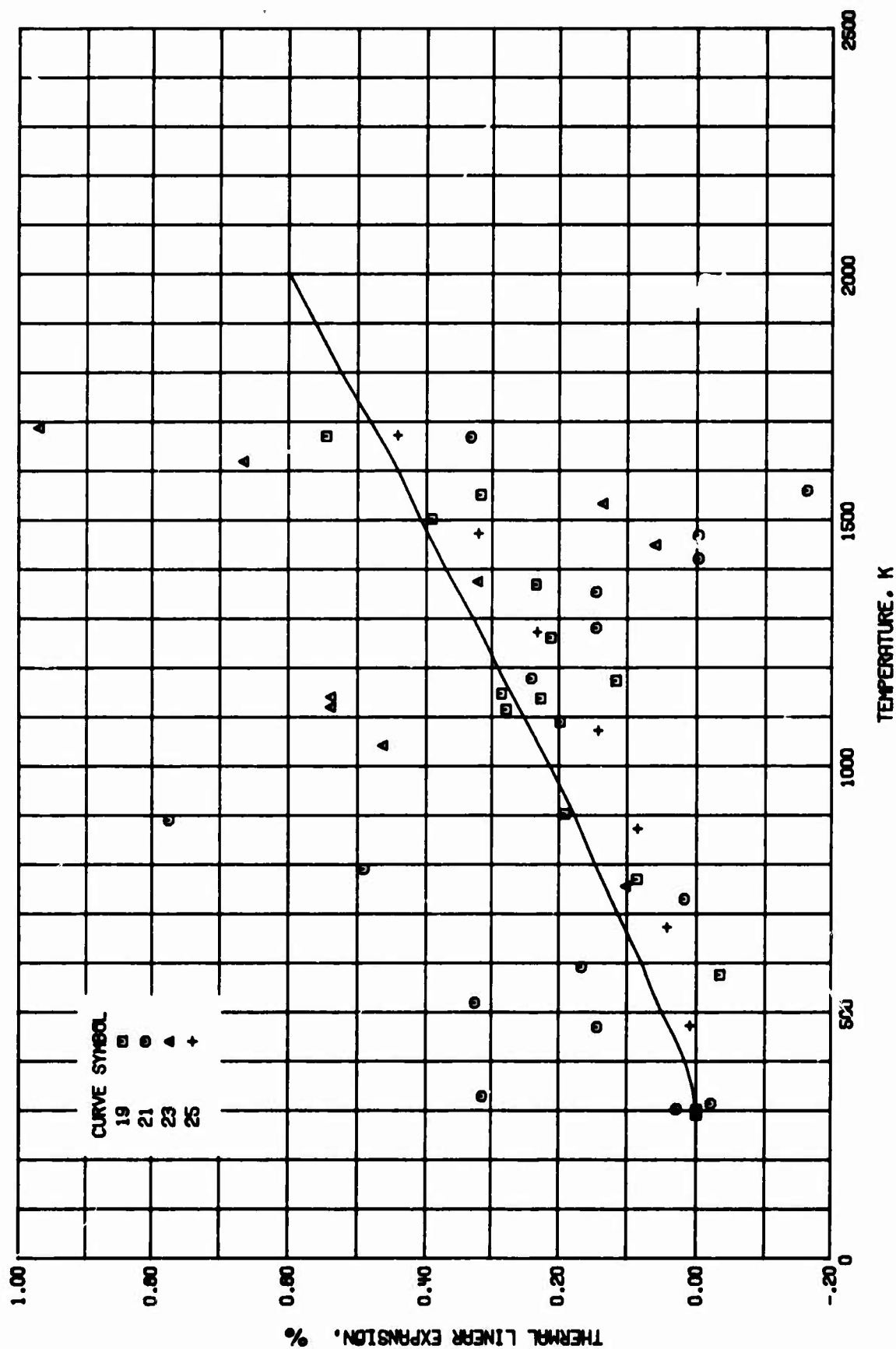


FIGURE 4-36. THERMAL LINEAR EXPANSION OF ALPHA-SILICON NITRIDE PARALLEL TO C-AXIS .

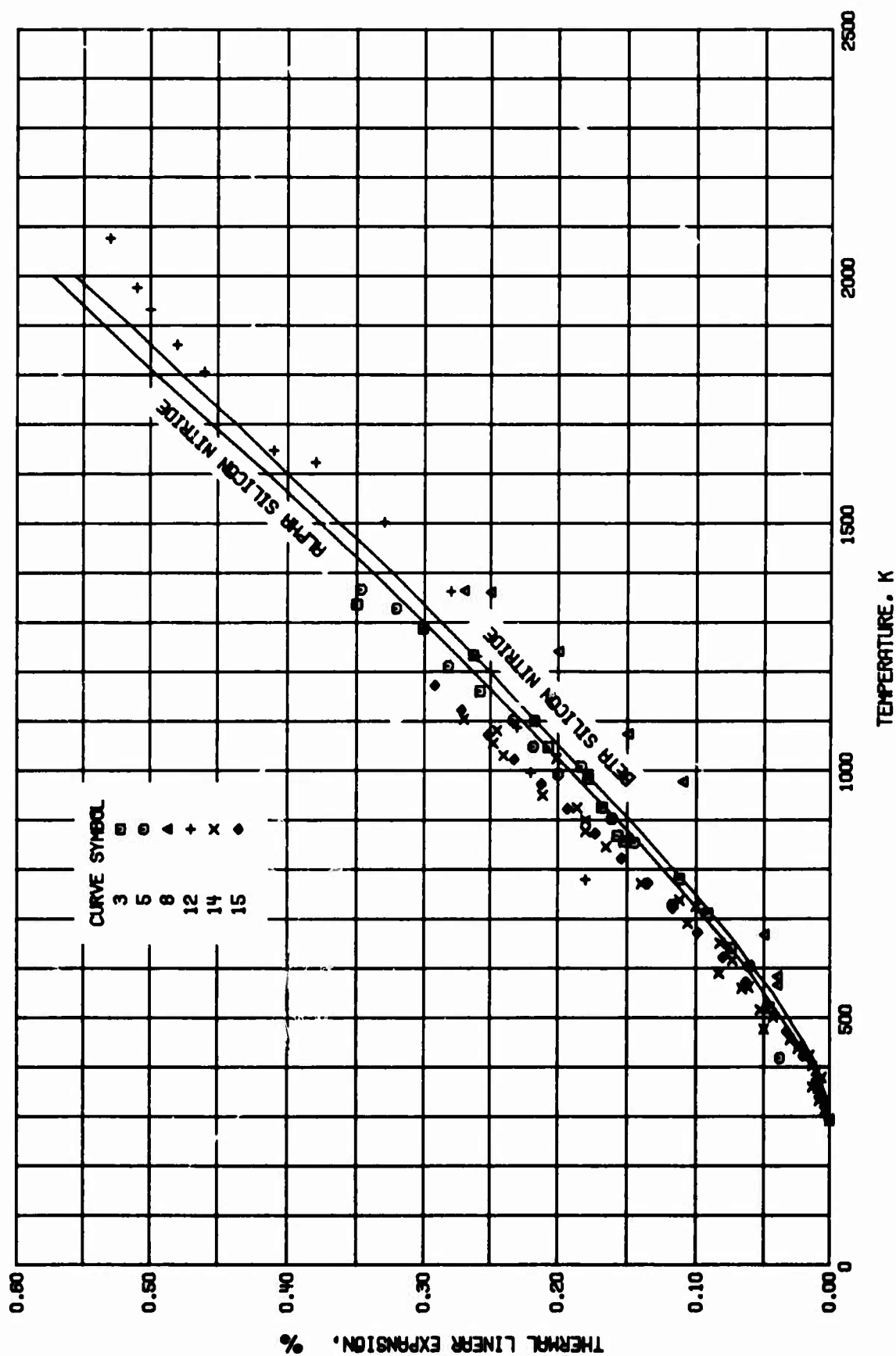


FIGURE 4-3C. THERMAL LINEAR EXPANSION OF POLYCRYSTALLINE SILICON NITRIDE .

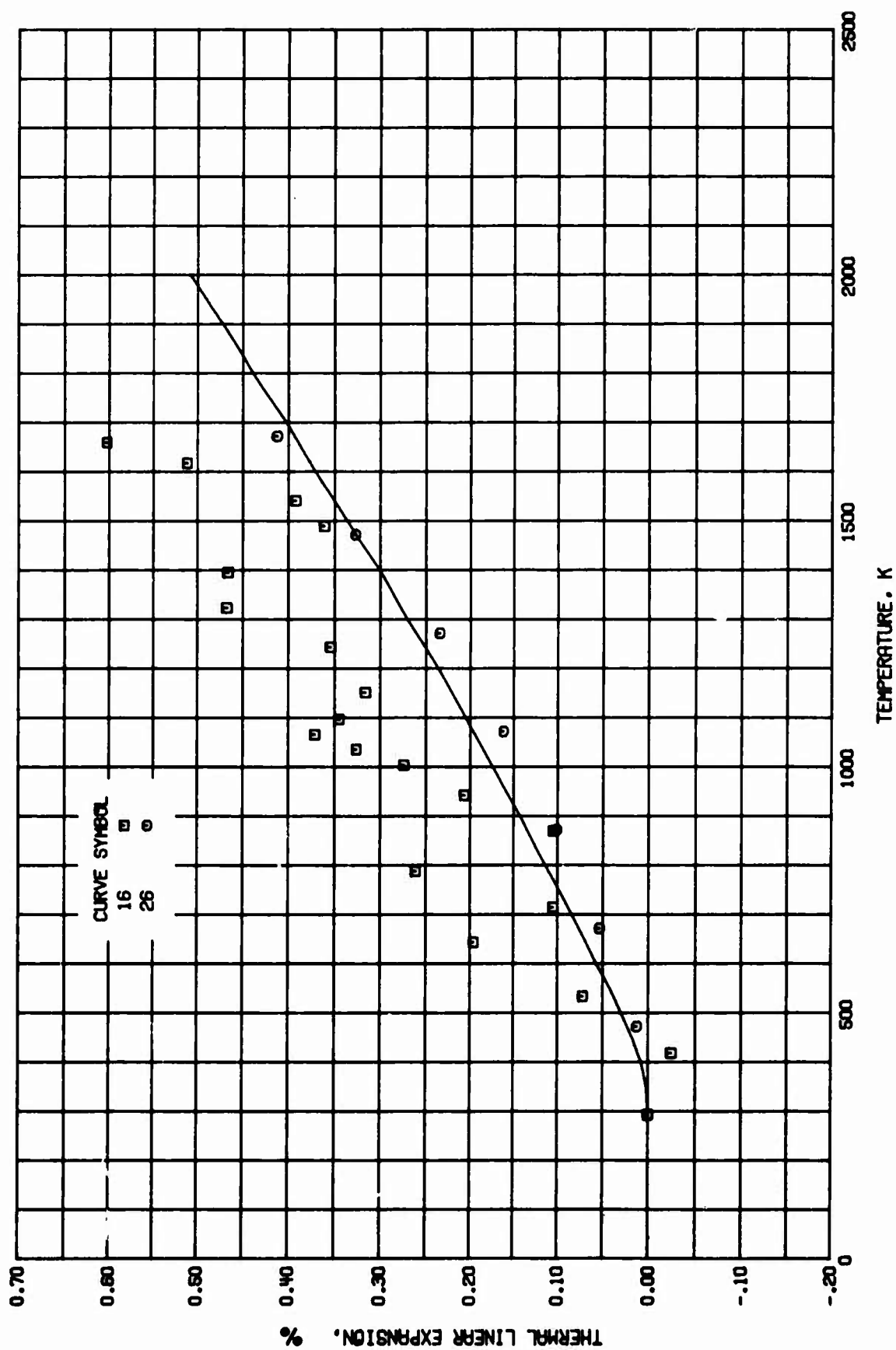


FIGURE 4-30. THERMAL LINEAR EXPANSION OF BETA-SILICON NITRIDE PARALLEL TO A-AXIS .

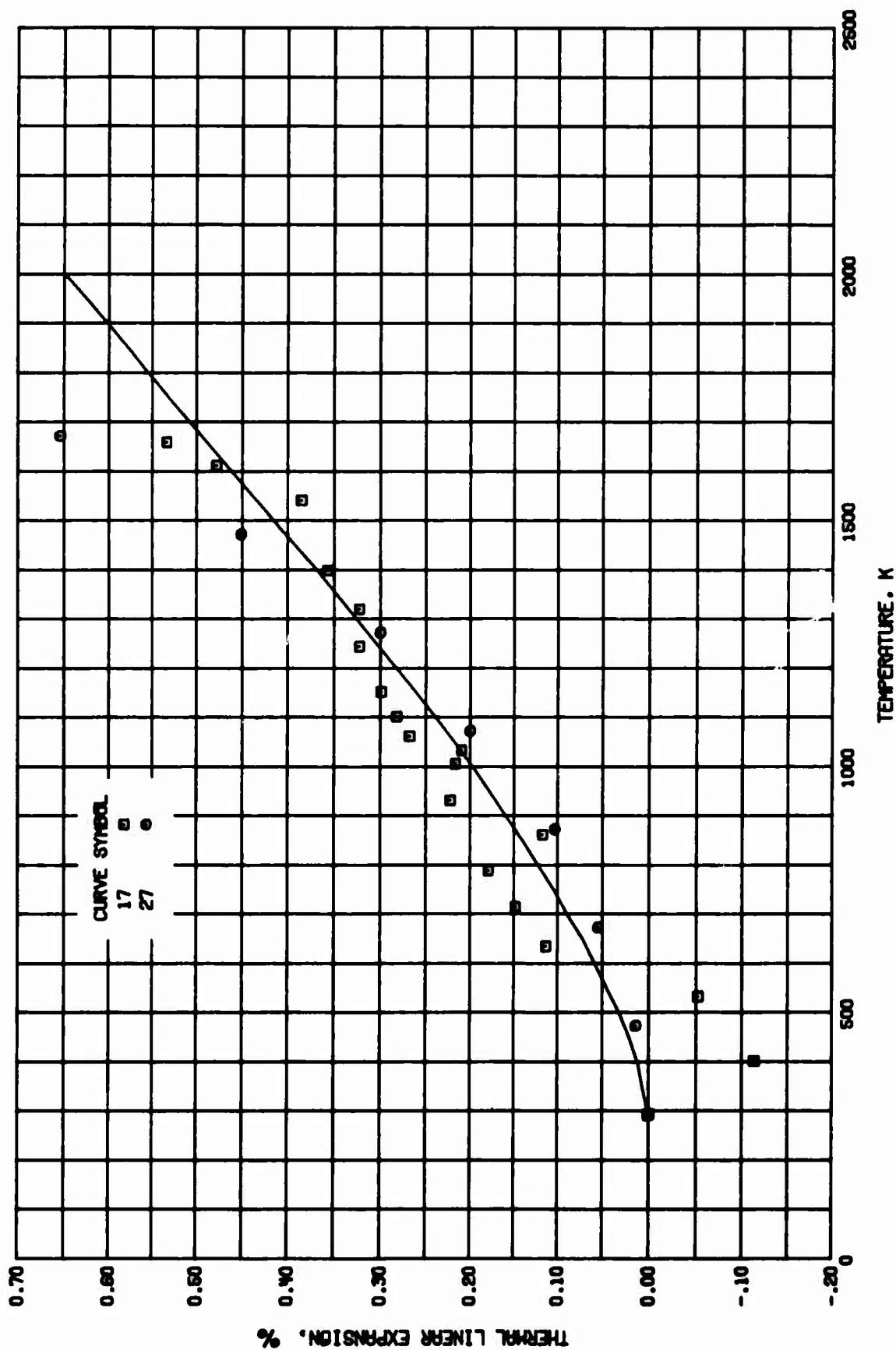


FIGURE 4-3E. THERMAL LINEAR EXPANSION OF BETA-SILICON NITRIDE PARALLEL TO C-AXIS .

TABLE 4-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	Tomiyama, T., Fujii, Y., Sugita, Y., and Kishino, S.	1967	X	1073, 1273		Film deposited through chemical reaction of SiH_4 and NH_3 at 1073 K on surface of the silicon substrate of the (111) surface cut along [110] direction to the dimension of 20 x 5 mm; oxidized in steam at 1073 K and 1273 K respectively; thermal expansion coefficient of films using coefficient of substrates; $\Delta L/L_0 = 0.252$ at 1073 K \approx assumed.
2*	Steele, S. R., Pappas, J., Schilling, H., and Hagan, L.	1967		273-1273		Specimen deposited from vapor at 1323-1573 K.
3	Wells, W. M.	1964		521-1337		Specimen 4 in. x 0.5 in. x 0.5 in.; density 2.3 g cm^{-3} ; first run.
4*	Wells, W. M.	1964		531-1345		The above specimen; second run.
5	Wells, W. M.	1964		419-1367		The above specimen; third run.
6*	Wells, W. M.	1964		1048-1359		The above specimen; fourth run.
7*	Wells, W. M.	1964		863-1763		Similar to the above specimen; data taken using less precise apparatus.
8	Neel, D. S., Pears, C. D., and Ogleby, S., Jr.	1962	L	294-1365		Calculated composition before exposure 60.06 Si and 39.91 N, Carborundum Co.; initial length 7.58 cm; elements found by semi-quantitative emission spectroscopy, 0.7 Fe, 0.6 Ca, 0.03 Al, 0.1 each Mn, Mg, Cr, Zr, and traces of Ti; after exposure 0.49 C; formed by A casting; density before exposure 2.5 g cm^{-3} at 298 K; measurements in helium atm.
9*	Neel, D. S., et al.	1962	L	1365-796		Cooling the above specimen to 796 K.
10*	Neel, D. S., et al.	1962	L	796-1376		Reheating the above specimen to 1375 K.
11*	Neel, D. S., et al.	1962	L	1375-780		Recooling the above specimen to 780 K.
12	Neel, D. S., et al.	1962	L	780-2078		Final heating the above specimen.
13*	Neel, D. S., et al.	1962	L	2078-294		Final cooling the above specimen; specimen found broken on post inspection.
14	Burkhardt, P. J. and Marvel, R. F.	1969		293-1105		98.0 Si_3N_4 with impurities of Mo, Cl, O, Ca, and Al detected by electron microprobe; sample film prepared by sputtering 1-2 μ thick onto strip of annealed molybdenum metal of 0.5 in. wide, 3 in. long, and 0.003 in. thick, and then rolled over edge to provide lateral curvature; cathetometer used to measure distance between two reference marks as function of temperature on freely suspended strip of film.
15	Gregor, L. V.	1968	T	293-1104		Film specimen obtained by sputtering particles onto surface and stripping film off; specimen 7.63 cm x 1.27 cm x 1.5 μ thick; film suspended vertically for measurements.
16	Thompson, D. S. and Pratt, P. L.	1965	X	293-1669	β - Si_3N_4	No information on the specimen reported, measured along a-axis; lattice parameter reported at 293 K is 7.5968 Å.
17	Thompson, D. S. and Pratt, P. L.	1965	X	293-1659	β - Si_3N_4	Measured along c-axis; lattice parameter reported at 293 K is 2.9087 Å.

* Not shown in figure.

TABLE 4-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4 (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1674	$\alpha\text{-Si}_3\text{N}_4$	No information on the specimen reported, measured along a-axis $L/8$ $3\frac{1}{8}$ Si; lattice parameter reported at 293 K is 7.7534 Å; observed peak may be due to diffused oxygen atoms forming bonds with Si atoms.
19 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1671	$\alpha\text{-Si}_3\text{N}_4$	The above specimen except measured along c-axis; lattice parameter reported at 293 K is 7.6046 Å.
20 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1669	$\alpha\text{-Si}_3\text{N}_4$	The above specimen except $L/6$ $5\frac{1}{8}$ Si; measured along a-axis; lattice parameter reported at 293 K is 7.7508 Å.
21 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1669	$\alpha\text{-Si}_3\text{N}_4$	The above specimen except measured along c-axis; lattice parameter reported at 293 K is 5.6004 Å.
22 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1712	$\alpha\text{-Si}_3\text{N}_4$	The above specimen except $L/3$ $1\frac{1}{8}$ Si; measured along a-axis; lattice parameter reported at 293 K is 7.7508 Å.
23 113	Thompson, D. S. and Pratt, P. L.	1965	X	293-1688	$\alpha\text{-Si}_3\text{N}_4$	The above specimen except $L/3$ $1\frac{1}{8}$ Si; measured along c-axis; lattice parameter reported at 293 K is 5.5956 Å.
24 114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	$\alpha\text{-Si}_3\text{N}_4$	Specimen prepared by heating pure Si and nitrogen at 1673 K; measured along a-axis; lattice parameter reported at 293 K is 7.7500 Å.
25 114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	$\alpha\text{-Si}_3\text{N}_4$	The above specimen; measured along c-axis; lattice parameter reported at 293 K is 5.6146 Å.
26 114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	$\beta\text{-Si}_3\text{N}_4$	Specimen prepared by heating pure Si and nitrogen at 1673 K; measured along a-axis; lattice parameter reported at 293 K is 7.6048 Å.
27 114	Iwai, S. and Yasunaga, A.	1959	X	273-1673	$\beta\text{-Si}_3\text{N}_4$	The above specimen; measured along c-axis; lattice parameter reported at 293 K is 2.9042 Å.
28* 115	Carr, E. M. and Bartlett, R. W.	1968		293-1273		Duplex silicon nitride; three 1.875 O.D. ring specimens; 2.55, 2.54, and 2.51 g cm ⁻³ densities which were cut from an isotastically pressed cylinder and were fired for 20 hr at 1523 K, then 8 hr at 1723 K before the measurements of change in diameter; during test each specimen underwent two complete thermal cycles between 293 and 1273 K.
29* 105	McLennan, A. F., Fisher, E. A., and Bratton, R. J.	1973	L	293-1714 B2, 1:A9		Hot pressed specimen; expansion for sample 2, billet 1 in the direction parallel to hot press direction is same as for sample 9 in the direction perpendicular to hot press direction.
30* 105	McLennan, A. F., et al.	1973	L	293-1716 A10		Similar to the above specimen; expansion for sample 10 in the direction perpendicular to hot press direction.
31* 105	McLennan, A. F., et al.	1973	L	293-1714 B10		The above specimen; expansion in the direction parallel to hot press direction.
32* 105	McLennan, A. F., et al.	1973	L	293-1720 B9		Similar to the above specimen; expansion for sample 9 in the direction parallel to hot press direction.
33* 105	McLennan, A. F., et al.	1973	L	293-1705 A2, 1		Similar to the above specimen; expansion for sample 2, billet 1 in the direction perpendicular to hot press direction.

* Not shown in figure.

TABLE 4-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4
 [Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %]

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
<u>CURVE 1*</u>		<u>CURVE 5 (cont.)</u>		<u>CURVE 10 (cont.)*</u>		<u>CURVE 14 (cont.)</u>		<u>CURVE 15 (cont.)</u>	
1073	0.252	993	0.200	1087	0.21	393	0.010	1073	0.252
1273	0.329	1049	0.218	1235	0.25	425	0.013	1123	0.272
<u>CURVE 2*</u>		1103	0.233	1374	0.27	438	0.015	1173	0.292
273	-0.012	1212	0.282	<u>CURVE 11*</u>		446	0.024	<u>CURVE 16</u>	
1273	0.588	1329	0.321	1374	0.27	456	0.023	293	0.000
<u>CURVE 3</u>		1367	0.347	1180	0.25	477	0.030	419	-0.024
521	0.046	<u>CURVE 6*</u>		1121	0.23	502	0.043	534	0.072
642	0.075	1049	0.187	1074	0.22	516	0.053	534	0.072
711	0.092	1143	0.233	1033	0.21	560	0.067	644	0.196
781	0.112	1262	0.278	845	0.18	562	0.062	715	0.105
857	0.152	1302	0.299	831	0.18	590	0.084	788	0.261
869	0.157	1328	0.317	780	0.18	617	0.074	870	0.105
926	0.168	1359	0.321	294	0.00	651	0.083	943	0.207
984	0.178	<u>CURVE 7*</u>		681	0.106	681	0.106	1004	0.274
1009	0.183	863	0.158	726	0.100	726	0.100	1036	0.326
1048	0.207	1144	0.279	738	0.112	738	0.112	1066	0.371
1101	0.217	1266	0.331	772	0.140	772	0.140	1097	0.345
1161	0.258	1423	0.360	846	0.165	846	0.165	1152	0.316
1234	0.263	1481	0.405	1088	0.23	877	0.180	1244	0.354
1289	0.301	1536	0.447	1232	0.26	900	0.180	1324	0.467
1337	0.350	1596	0.513	1363	0.28	925	0.186	1396	0.466
<u>CURVE 4*</u>		1650	0.513	1503	0.33	950	0.211	1490	0.361
531	0.039	1763	0.536	1624	0.38	1025	0.201	1542	0.392
724	0.093	<u>CURVE 8</u>		1648	0.41	1031	0.240	1618	0.512
795	0.122	294	0.00	1837	0.46	1056	0.248	1660	0.603
993	0.192	567	0.04	1862	0.48	1082	0.245	<u>CURVE 17</u>	
1070	0.218	585	0.04	1933	0.50	1105	0.270	293	0.000
1113	0.224	668	0.05	1977	0.51	<u>CURVE 15</u>		401	-0.114
1173	0.255	978	0.11	2077	0.53	293	0.000	532	-0.052
1217	0.262	1075	0.15	<u>CURVE 13*</u>		336	0.004	634	0.113
1250	0.267	1242	0.20	2077	0.53	373	0.010	714	0.148
1310	0.296	1362	0.25	294	0.20	423	0.020	788	0.179
1345	0.320	1365	0.27	<u>CURVE 14</u>		473	0.033	861	0.117
<u>CURVE 5</u>		<u>CURVE 9*</u>		293	0.000	523	0.048	931	0.223
419	0.038	293	0.000	312	0.004	623	0.064	1006	0.217
605	0.061	312	0.004	333	0.008	673	0.081	1033	0.210
729	0.117	796	0.16	358	0.008	723	0.117	1062	0.268
854	0.145	<u>CURVE 10*</u>		360	0.013	773	0.135	1101	0.282
903	0.161	796	0.16	366	0.008	823	0.154	1152	0.299
<u>CURVE 18</u>		<u>CURVE 19</u>		379	0.006	873	0.173	1152	0.299
293	0.000	293	0.000	1023	0.232	923	0.193	1320	0.323
568	0.032	308	0.033	<u>CURVE 20</u>		939	0.357	1399	0.357
776	0.086	323	0.110	293	0.000	1541	0.385	1541	0.385
911	0.044	463	0.075	308	0.033	1612	0.478	1612	0.478
1036	0.246	510	0.048	323	0.110	1659	0.533	1659	0.533
1093	0.317	588	0.115	463	0.075	<u>CURVE 18</u>		293	0.000
1117	0.244	588	0.115	510	0.048	293	0.000	293	0.000
1133	0.319	588	0.115	588	0.115	308	0.033	308	0.033
1155	0.356	588	0.115	588	0.115	323	0.110	323	0.110
1176	0.303	588	0.115	588	0.115	463	0.075	463	0.075
1263	0.294	588	0.115	588	0.115	510	0.048	510	0.048
1368	0.334	588	0.115	588	0.115	588	0.115	588	0.115
1507	0.407	588	0.115	588	0.115	588	0.115	588	0.115
1556	0.352	588	0.115	588	0.115	588	0.115	588	0.115
1674	0.411	588	0.115	588	0.115	588	0.115	588	0.115

* Not shown in figure.

TABLE 4-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF SILICON NITRIDE Si_3N_4 (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 20 (cont.)		CURVE 23 (cont.)		CURVE 27 (cont.)		CURVE 31*		CURVE 33 (cont.)*	
1184	-0.081	1121	0.540	673	0.055	293	0.000	1373	0.331
1291	0.013	1142	0.540	873	0.103	373	0.014	1473	0.376
1361	0.028	1376	0.322	1073	0.200	473	0.033	1573	0.425
1418	-0.053	1450	0.061	1273	0.300	573	0.058	1673	0.476
1476	0.013	1534	0.136	1473	0.451	673	0.085	1705	0.494
1561	0.093	1620	0.665	1673	0.654	773	0.111		
1675	0.274	1698	0.972			873	0.139		
CURVE 21		CURVE 24		CURVE 28*		973	0.171		
293	0.000	273	0.000	293	0.000	1073	0.203		
303	0.029	293	0.000	1273	0.441	1173	0.240		
314	-0.021	473	0.003			1273	0.275		
329	0.314	673	0.004	CURVE 29*		1373	0.316		
470	0.143	873	0.008	293	0.000	1473	0.360		
519	0.325	1073	0.013	373	0.017	1573	0.404		
592	0.166	1273	0.022	473	0.040	1673	0.451		
730	0.018	1473	0.032	573	0.064	1714	0.472		
792	0.491	1673	0.044	673	0.091	CURVE 32*			
891	0.775			773	0.118	293	0.000		
998	1.123	CURVE 25		873	0.149	373	0.011		
1069	1.514	273	-0.009	973	0.182	473	0.027		
1179	0.241	293	0.000	1073	0.214	573	0.045		
1281	0.145	473	0.009	1173	0.247	673	0.068		
1354	0.145	673	0.043	1273	0.282	773	0.093		
1422	-0.002	873	0.085	1373	0.324	873	0.120		
1469	-0.002	973	0.085	1473	0.368	973	0.150		
1560	-0.162	1073	0.142	1573	0.412	1073	0.182		
1609	0.332	1273	0.232	1673	0.460	1173	0.214		
CURVE 22		1473	0.321	1714	0.481	1273	0.250		
293	0.000	1673	0.443	CURVE 30*		1373	0.292		
754	0.206	CURVE 26		293	0.000	1473	0.336		
955	0.224	273	-0.003	373	0.014	1573	0.383		
1043	0.515	293	0.000	473	0.028	1673	0.433		
1097	0.489	473	0.013	573	0.050	1720	0.457		
1382	0.142	673	0.054	673	0.075	CURVE 33*			
1454	0.010	873	0.101	773	0.103	293	0.000		
1544	0.267	973	0.162	873	0.131	373	0.015		
1621	0.280	1073	0.235	973	0.162	473	0.034		
1712	0.262	1273	0.327	1073	0.194	573	0.058		
CURVE 23		1473	0.412	1173	0.229	673	0.085		
293	0.000	1673	0.412	1273	0.267	773	0.114		
303	0.000	CURVE 27		1373	0.308	873	0.145		
797	0.102	273	0.000	1473	0.350	973	0.178		
1043	0.465	293	0.000	1573	0.395	1073	0.212		
		473	0.014	1673	0.441	1173	0.250		
				1716	0.464	1273	0.289		

* Not shown in figure.

e. Thermal Diffusivity

There are twelve sets of data available for the thermal diffusivity of porous silicon nitride, ten of which consist of a single data point each at room temperature. The experimental data are tabulated in Table 4-12. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 4-11. The porosity of the various specimens reported varies between 17% and 85%. The available information is not adequate for analysis. Hence the thermal diffusivity values are calculated from the equation:

$$\alpha = \frac{k}{C_p d}$$

using the values of thermal conductivity, specific heat, and thermal linear expansion reported in earlier sections. The resulting values are tabulated in Table 4-10 and shown in Figure 4-4 and are for polycrystalline samples with densities 2.4 g cm^{-3} and 3.16 g cm^{-3} . Since the values are very uncertain, they are considered merely as typical values.

TABLE 4-10. TYPICAL THERMAL DIFFUSIVITY OF SILICON NITRIDE (Si_3N_4)[Temperature, T, K; Thermal Diffusivity, α , $\text{cm}^2 \text{s}^{-1}$]

T	α	
	Density 2.4 g cm^{-3}	Density 3.16 g cm^{-3}
293	0.0989	0.162
300	0.0963	0.157
350	0.0835	0.137
400	0.0742	0.121
450	0.0662	0.108
500	0.0598	0.0984
550	0.0545	0.0894
600	0.0503	0.0822
650	0.0467	0.0764
700	0.0433	0.0708
750	0.0406	0.0667
800	0.0387	0.0636
850	0.0365	0.0599
900	0.0347	0.0570
950	0.0330	0.0540
1000	0.0317	0.0520
1100	0.0293	0.0480
1200	0.0273	0.0447
1300	0.0258	0.0420
1400	0.0245	0.0397
1500	0.0232	0.0377
1600	0.0222	0.0360
1700	0.0213	0.0347
1800	0.0205	0.0333
1900	0.0196	0.0322
2000	0.0190	0.0318

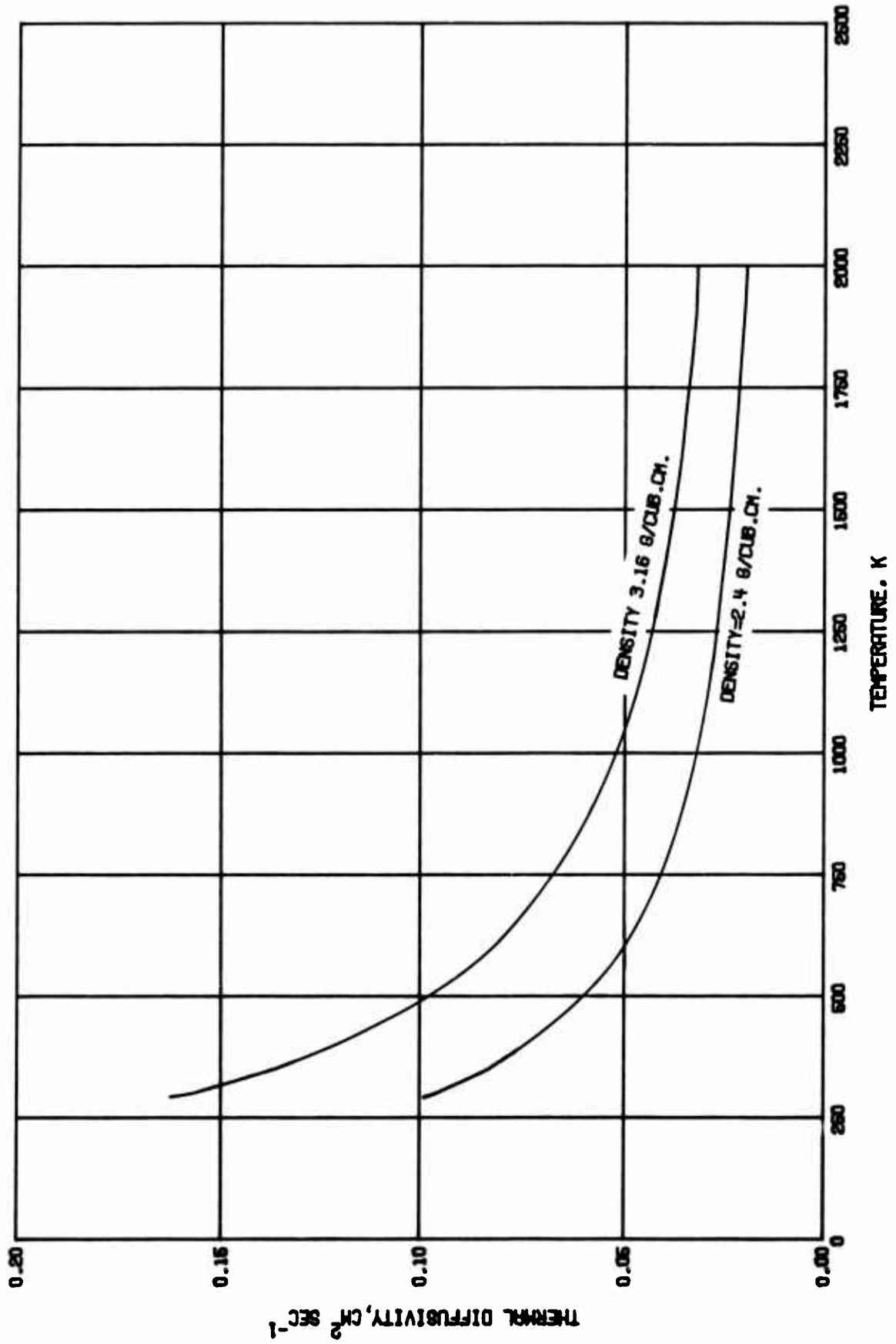


FIGURE 4-4. THERMAL DIFFUSIVITY OF POLYCRYSTALLINE SILICON NITRIDE.

TABLE 4-11. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF SILICON NITRIDE Si_3N_4

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	Swarts, E. L. and Crandall, W. B.	1951		1173, 1673		Porosity 70%.
2*	Swarts, E. L. and Crandall, W. B.	1951		1173		Porosity 85%.
3*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1471	Flame-sprayed; density 2.84 g cm ⁻³ .
4*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1473	Density 1.99 g cm ⁻³ .
5*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1474	Density 2.00 g cm ⁻³ .
6*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1475	Density 2.34 g cm ⁻³ .
7*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1478	Density 2.43 g cm ⁻³ .
8*	Godfrey, D. J. and Lindley, M. W.	1972		298	AML 1482	Density 2.63 g cm ⁻³ .
9*	Godfrey, D. J. and Lindley, M. W.	1972		298	AME	Density 2.52 g cm ⁻³ .
10*	Godfrey, D. J. and Lindley, M. W.	1972		298	BSA	Density 2.47 g cm ⁻³ .
11*	Godfrey, D. J. and Lindley, M. W.	1972		298	Lucas	Flame-sprayed; density 2.58 g cm ⁻³ .
12*	Godfrey, D. J. and Lindley, M. W.	1972		298	Lucas	Hot-pressed; density 3.07 g cm ⁻³ .

TABLE 4-12. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF SILICON NITRIDE Si_3N_4 [Temperature, T, K; Thermal Diffusivity, α , cm² s⁻¹]

T	α	T	α
CURVE 1*		CURVE 10*	
1173	0.0110	298	0.086
1673	0.0055	CURVE 11*	
CURVE 2*		298	0.124
1173	0.0063	CURVE 12*	
CURVE 3*		298	0.155
298	0.191	CURVE 8*	
CURVE 4*		298	0.145
298	0.056	CURVE 9*	
		298	0.083

* Not shown in figure.

3.5. Boron Fiber Epoxy Composite

This composite material consists usually of continuous boron filaments surrounded by a matrix of epoxy resin. It is usually produced in tape form so that it can be used in further fabrication of specialized materials.

The boron filaments, as currently produced, are formed by vapor deposition of boron on a fine tungsten wire substrate within a reactor. Exposure of the tungsten substrate to the high-temperature boron trichloride reactor environment results in a filament consisting of a boron sheath on a tungsten boride core. Other means of producing boron filaments are currently being investigated which would eliminate the tungsten substrate.

The organic matrix resins most commonly used with boron filaments are modified epoxy resins, available as commercial formulations developed specifically for this purpose. Other organic resins used include polyamides and phenolics. However, the state of the art with these resins is less advanced than for the epoxy resins.

The normal service temperature range of the boron fiber epoxy composite is dependent on the type of epoxy resin being used as a matrix. This range is from about 220 K, below which the epoxy becomes very brittle, to 450 K. Epoxy resin decomposes around 590 K.

a. Thermal Conductivity

There are three sets of data available for the thermal conductivity of boron fiber epoxy composite. The experimental data are tabulated in Table 5-3 and shown in Figure 5-1. The information on specimen characterization and measurement condition is given in Table 5-2. The data reported by Gille [116] (curve 1) is for a composite with epoxy content of 32.5%. Hertz et al. [117] (curves 2 and 3) did not report the composition of their specimens for thermal conductivity measurements; however, most of their specimens for other tests (e.g. mechanical strength) are for composites with approximate epoxy content of 33%. It is therefore assumed that their thermal conductivity measurements are for specimens with the same epoxy content, i. e. 33%.

The provisional values tabulated in Table 5-1 and shown in Figure 5-1 are based on the investigations of Gille (curve 1) for heat flow in the direction parallel to the boron fibers, and on those of Hertz et al. (curve 2) for heat flow in the direction perpendicular to the boron fibers. The data of Hertz et al. (curve 3) for heat flow in the

parallel direction are ignored because their data show a wild temperature dependence at around 350 K. The tabulated values are for a composite with epoxy content of about 30%. Their uncertainty is estimated to be $\pm 25\%$.

TABLE 5-1. PROVISIONAL THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, $\text{W cm}^{-1} \text{K}^{-1}$]

T	k	
	30 volume percent epoxy	
	a	b
40	0.0151	0.0029
60	0.0184	0.0031
80	0.0201	0.0034
100	0.0210	0.0037
120	0.0215	0.0039
150	0.0219	0.0043
200	0.0223	0.0049
250	0.0226	0.0054
293	0.0228	0.0058
300	0.0229	0.0059
350	0.0230	0.0061
400	0.0228	0.0060
450	0.0224	0.0051

a Heat flow parallel to fiber direction.

b Heat flow perpendicular to fiber direction.

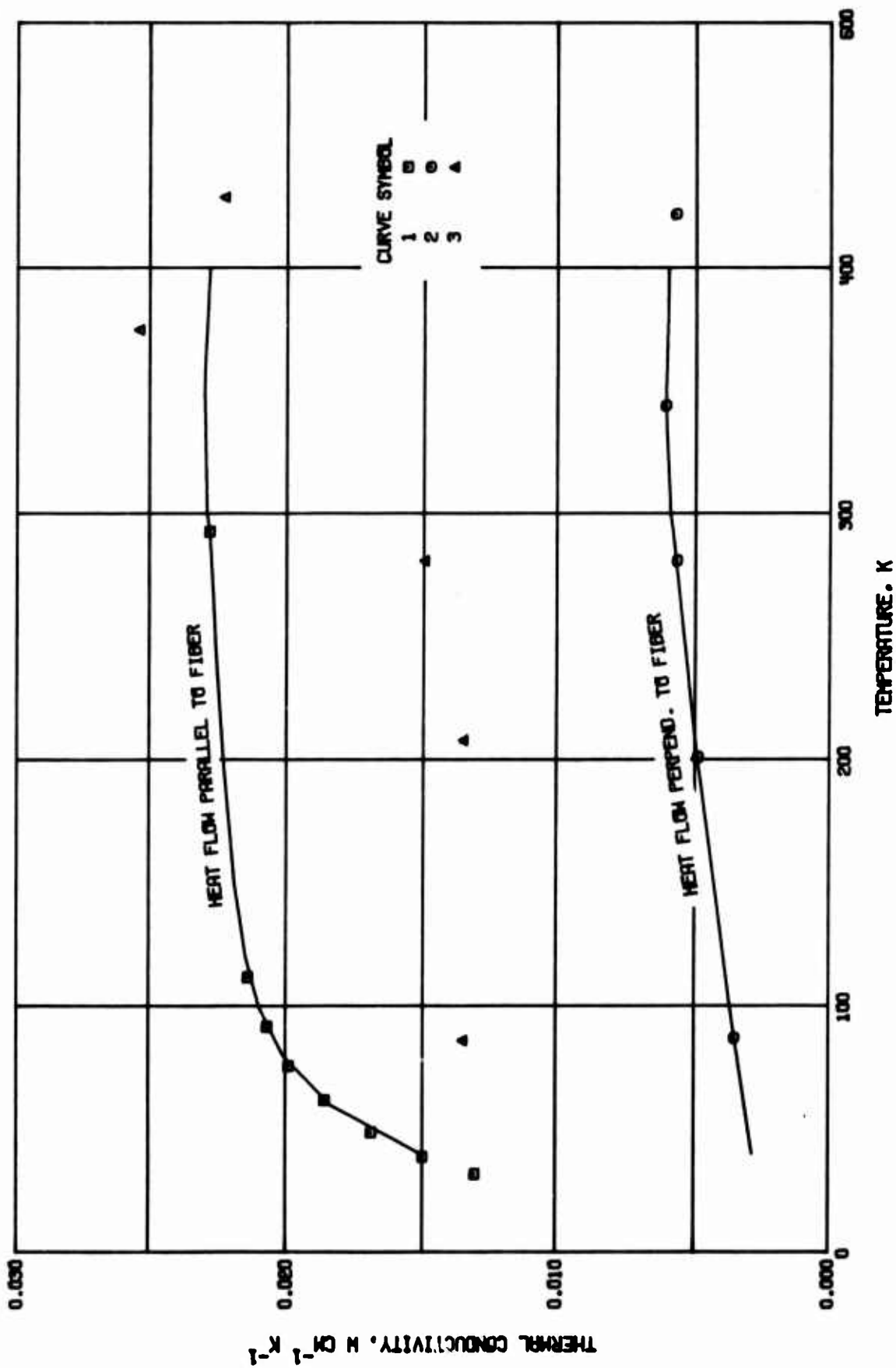


FIGURE 5-1. THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITES.

TABLE 5-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	Gille, J. P.	1969	L	32-293	4	67.5% 0.004 in. boron fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.005 in. I.D., 1.143 in. O.D., and 0.540 in. h; effective length; density 2.08 g cm ⁻³ ; heat flow parallel to fibers; data taken from smooth curve.
2	Hertz, J., Christian, J. L., and Varlas, M.	1972	L	87-422	SP-272	8 x 8 x 0.5 in. unidirection panel; heat flow perpendicular to fibers.
3	Hertz, J., et al.	1972	L	85-429	SP-272	Similar to the above specimen but heat flow parallel to fibers.

TABLE 5-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹]

T	k	T	k
<u>CURVE 1</u>		<u>CURVE 3</u>	
32	0.0130	86	0.0135
39	0.0150	208	0.0135
49	0.0169	281	0.0150
62	0.0186	375	0.0254
76	0.0199	429	0.0223
92	0.0207		
112	0.0214		
293	0.0228		
<u>CURVE 2</u>			
87	0.00355		
201	0.00489		
281	0.00567		
344	0.00609		
422	0.00573		

b. Specific Heat

There are 3 sets of experimental data available for the specific heat of boron fiber epoxy composite. The information on the specimen characterization and measurement conditions for each of the data sets are given in Table 5-5. The experimental data are tabulated in Table 5-6 and shown in Figure 5-2.

The provisional values tabulated in Table 5-4 and shown in Figure 5-2 are based on the measurements of Kim [118] (curve 1). The uncertainty of the values is about $\pm 7\%$. Hertz, Christian and Varlas [117] (curves 2 and 3) did not report the composition of their specimen, and therefore their results were not analyzed.

TABLE 5-4. PROVISIONAL SPECIFIC HEAT OF BCROF
FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p
	27 percent Epoxy
100	0.087
150	0.134
200	0.181
250	0.225
273.15	0.245
293	0.262
300	0.268
350	0.307
400	0.342
450	0.370

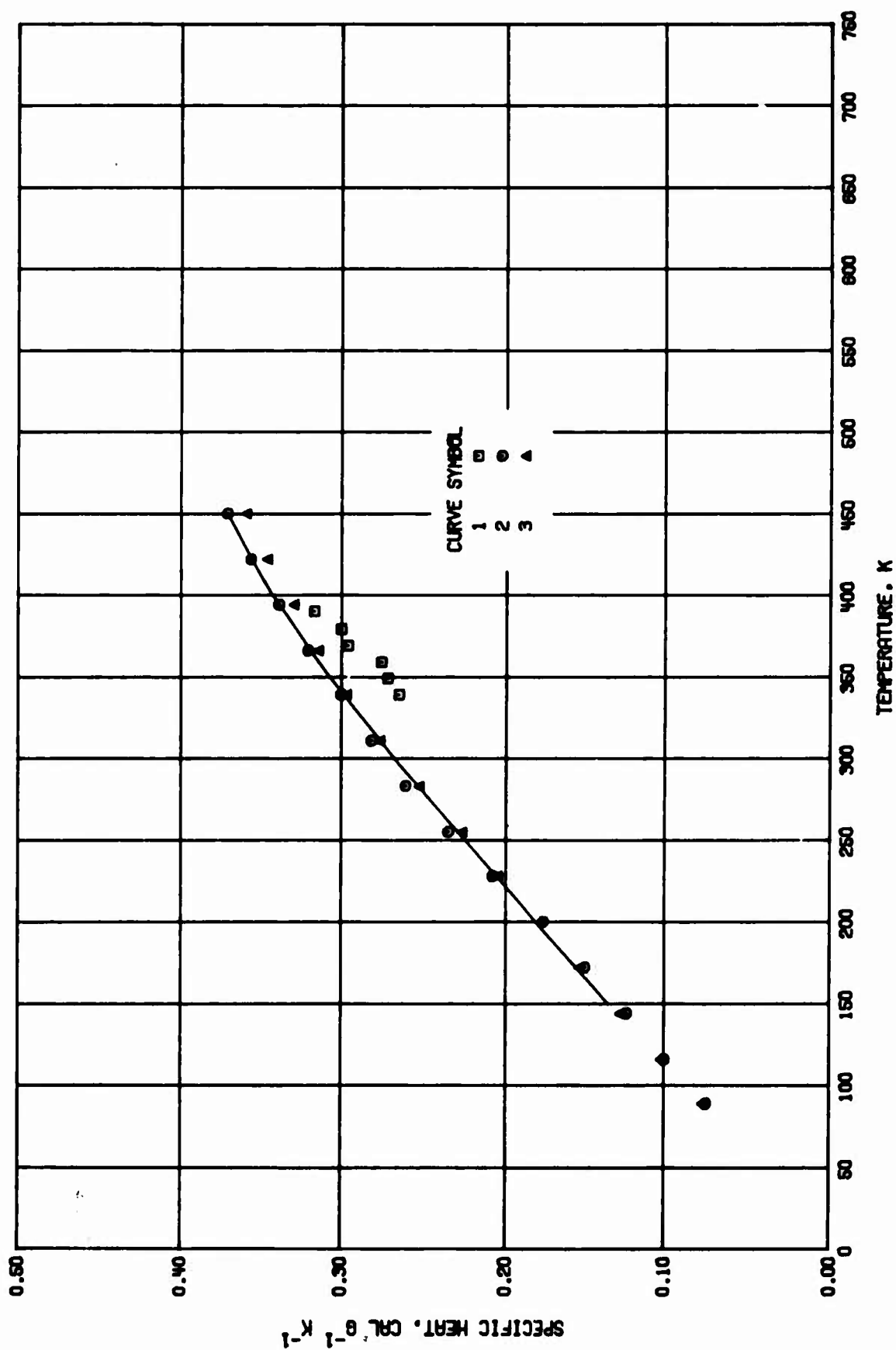


FIGURE S-2. SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITES .

TABLE 5-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 118	Kim, D. H.	1972	DSC	339-390	Specimen No. 11	Composite laminate consisted of SP272 epoxy and boron fibers; resin content 27.1 weight percent; density 1.890 g cm ⁻³ ; thickness 0.10 in. 3 M's SP-272 panel. Similar to the above specimen except water boiled for 24 hr.
2 117	Hertz, J., Christian, J. L., Varian, M.	1972		89-450	Panel 361-4	
3 117	Hertz, J., et al.	1972		89-450		

TABLE 5-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF BORON FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g⁻¹ K⁻¹]

T	C _p	T	C _p	T	C _p
<u>CURVE 1</u>		<u>CURVE 2 (cont.)</u>		<u>CURVE 3 (cont.)</u>	
339	0.265	339	0.300	366	0.314
349	0.272	366	0.320	394	0.329
359	0.276	394	0.338	422	0.345
369	0.296	422	0.355	450	0.358
379	0.300	450	0.370		
390	0.316				
<u>CURVE 2</u>		<u>CURVE 3</u>			
89	0.075	89	0.077		
116	0.100	116	0.102		
144	0.123	144	0.127		
172	0.149	172	0.153		
200	0.176	200	0.178		
228	0.206	228	0.205		
255	0.235	255	0.227		
283	0.261	283	0.253		
311	0.282	311	0.277		
		339	0.297		

c. Heat of Fusion

No experimental data for the heat of fusion of boron fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific epoxy resin, curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost and the specific properties desired in the cured resin. The softening point of cured resin is near 450 K. No experimental data for the heat of fusion/softening of cured epoxy resin were located in the literature. The melting point of boron is about 2300 K and its heat of fusion is $1110 \pm 40 \text{ cal g}^{-1}$.

d. Thermal Linear Expansion

There are 23 sets of experimental data available for the thermal linear expansion of boron fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets are given in Table 5-8. The experimental data are tabulated in Table 5-9 and shown partially in Figures 5-3A and 5-3B.

Nakamura and Larsen [119] (curves 1-3) reported the longitudinal and transverse thermal linear expansion data for Boron/Avco 5505 composite. Hertz et al. [117] (curves 4-23) reported data for SP-272 boron epoxy composites under various laminate orientations and experimental conditions. However, Hertz et al. [117] did not report the compositions of the specimens. Therefore, the provisional values tabulated in Table 5-7 and shown in Figures 5-3A and 5-3B are based on the data of Nakamura and Larsen [119] (curves 1 and 2), and are applicable to cured Boron/Avco 5505 composite with a density of 2 g cm^{-3} and a fiber content of about 50 volume percent. No experimental data for this Boron/Avco 5505 composite below 293 K were located in the literature. The low-temperature values were obtained by extrapolating the high-temperature values according to the general trend of the data for other composites. The uncertainty of the provisional values is about $\pm 10\%$.

The values of the instantaneous coefficient of thermal linear expansion, α , are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is within $\pm 20\%$.

TABLE 5-7. PROVISIONAL THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

T	a		b	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α
75	-0.041	1.0	-0.309	7
100	-0.038	1.3	-0.286	9
150	-0.031	1.6	-0.233	12
200	-0.022	2.0	-0.166	14
250	-0.011	2.5	-0.085	18
273.15	-0.005	2.7	-0.042	20
293	0.000	3.0	0.000	23
300	0.002	3.0	0.017	24
350	0.019	3.6	0.154	31
400	0.038	4.1	0.325	37
450	0.058	4.4	0.522	42

a Longitudinal thermal linear expansion.

b Transverse thermal linear expansion.

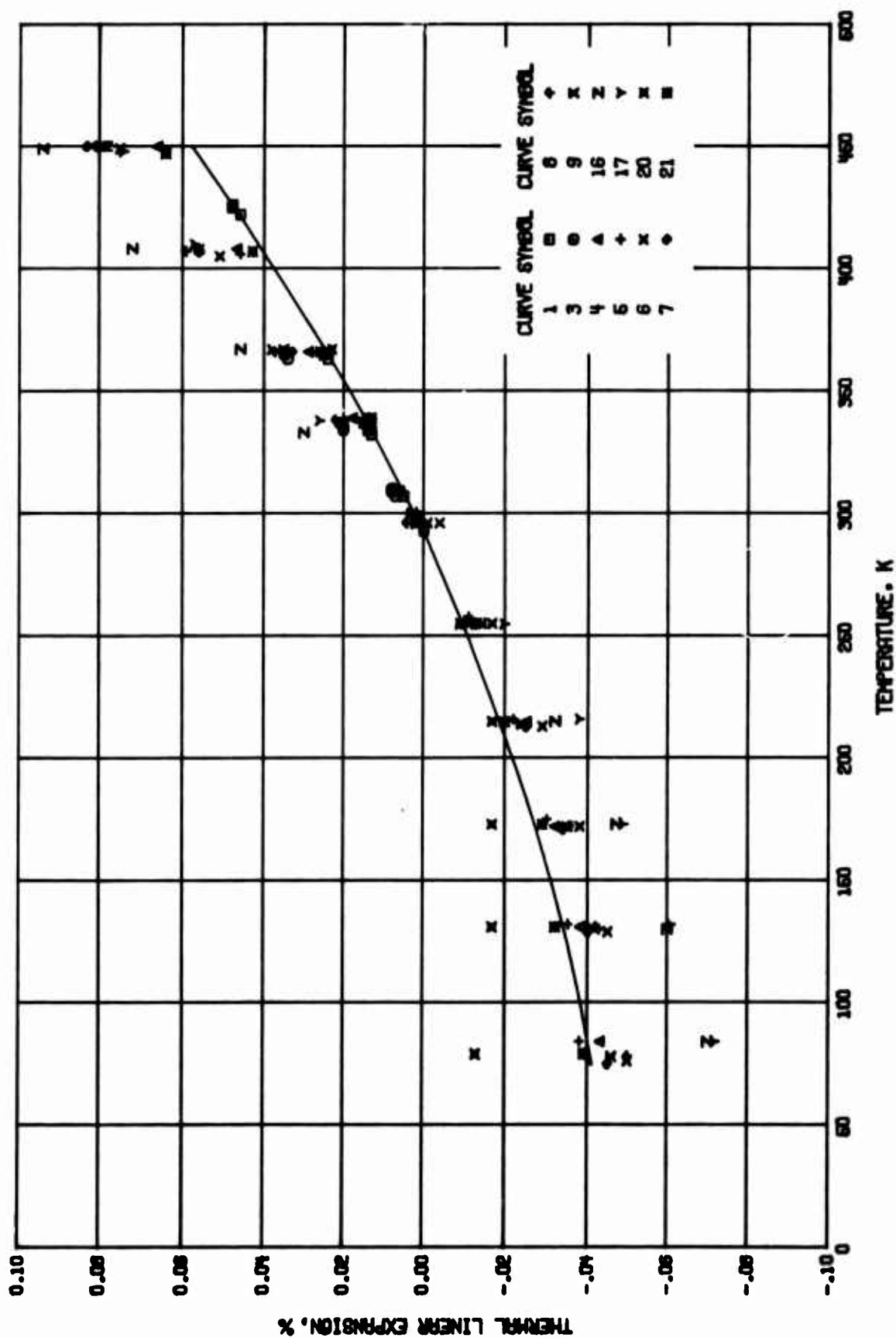


FIGURE 5-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES.

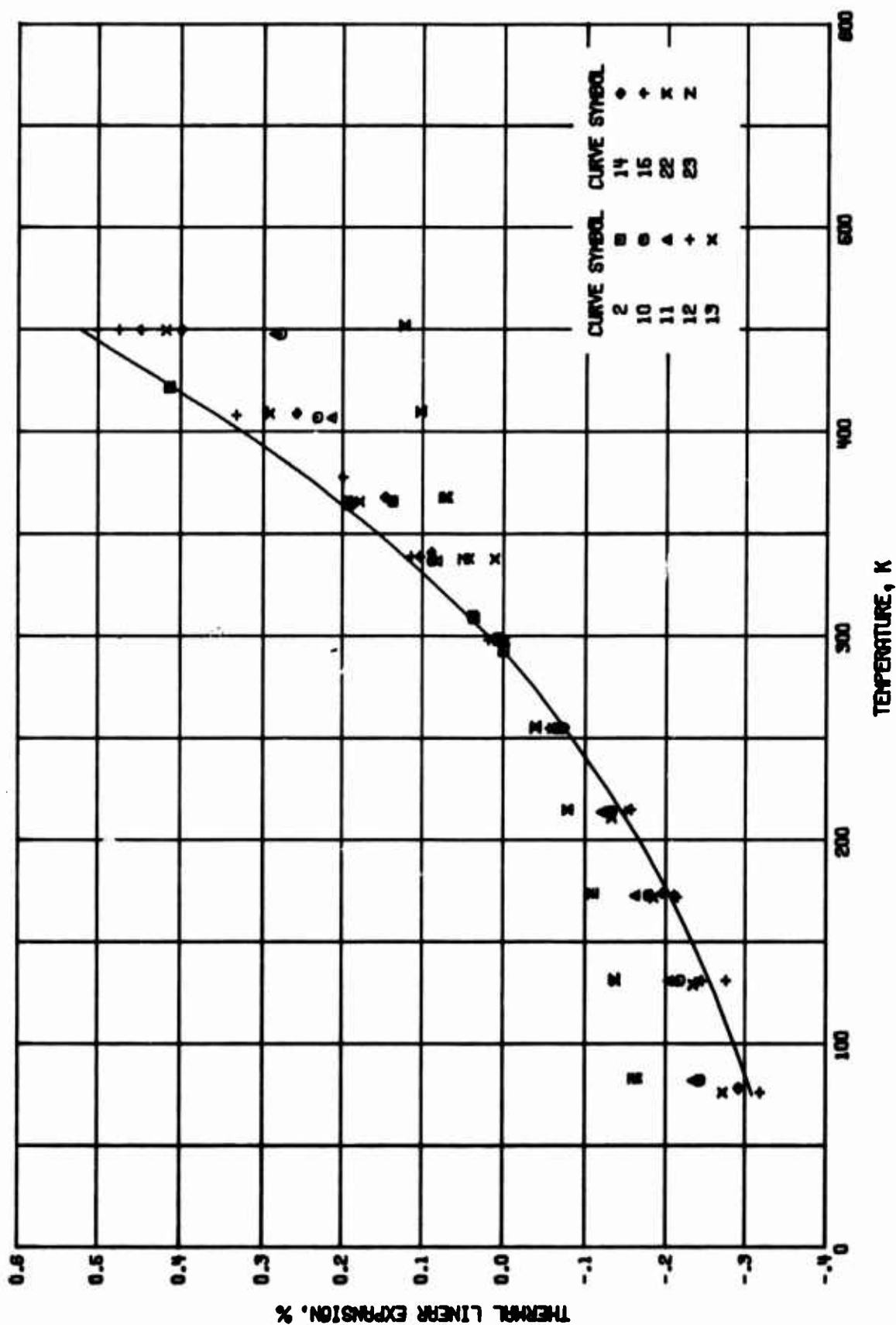


FIGURE 6-3B. TRANSVERSE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITES.

TABLE 5-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-426	Boron/Avco 5505	Boron/epoxy system of density 2 g cm^{-3} ; fiber tensile modulus $60 \times 10^4 \text{ psi}$; six ply of 0 deg (longitudinal) orientation; three specimens tested for each material orientation, reinforced epoxy laminates consisted of 5-7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; expansion in the specimen length direction measured for single $0.5 \times 2 \text{ in.}$ laminate roughly 0.050 in. thick; specimens cycled twice in air from ambient room temperature to 450 K ; values based on second cycle, stable behavior.
2 119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-422	Boron/Avco 5505	The above specimen except specimen eight ply of 90 deg (transverse) orientation; values based on second cycle, stable behavior.
3 119	Nakamura, H.H. and Larsen, D.C.	1974	L	293-366	Boron/Avco 5505	The above specimen except nine ply of balanced symmetric unidirectional-angle ply orientation designated $(0/45/135/0/90)_s$; plies stacked in directions $(0/+45/-45/0/90/-45/+45/0)$; individual ply thickness 5.8 mils ; values based on second cycle, stable behavior.
4 117	Hertz, J., Christian, J.L., and Varlan, M.	1972	L	84-450	NO558	SP-272 boron epoxy composite; panel B/EP-361-5; expansion for unidirectional laminate in 0 deg direction; zero-point correction 0.002%.
5 117	Hertz, J., et al.	1972	L	84-450	NO559	Similar to the above specimen and conditions; zero-point correction 0.003%.
6 117	Hertz, J., et al.	1972	L	76-450	Specimen No. 670	Similar to the above specimen and conditions; panel B/EP-410-2; zero-point correction 0.002%.
7 117	Hertz, J., et al.	1972	L	75-450	Specimen No. 667	Similar to the above specimen; last stable cycle; zero-point correction 0.007%.
8 117	Hertz, J., et al.	1972	L	78-450	Specimen No. 723	Similar to the above specimen; water boiled for 24 hr; zero-point correction 0.002%.
9 117	Hertz, J., et al.	1972	L	78-450	Specimen No. 719	Similar to the above specimen; specimen water boiled for 24 hr; zero-point correction 0.002%.
10 117	Hertz, J., et al.	1972	L	82-448	NO560	Similar to the above specimen; specimen water boiled for 24 hr; zero-point correction 0.002%.
11 117	Hertz, J., et al.	1972	L	82-448	NO561	Similar to the above specimen; panel B/EP-361-5; expansion for unidirectional laminate in 90 deg direction; zero-point correction 0.008%.
12 117	Hertz, J., et al.	1972	L	76-450	Specimen No. 668	Similar to the above specimen and conditions.
13 117	Hertz, J., et al.	1972	L	76-450	Specimen No. 669	Similar to the above specimen and conditions; zero-point correction 0.015%.
14 117	Hertz, J., et al.	1972	L	78-450	Specimen No. 721	Similar to the above specimen; panel B/EP-410-2; expansion for unidirectional lay up in 90 deg direction; last stable cycle; zero-point correction 0.025%.
15 117	Hertz, J., et al.	1972	L	78-450	Specimen No. 722	Similar to the above specimen and conditions; specimen water boiled for 24 hr.
16 117	Hertz, J., et al.	1972	L	84-449	NO546	Similar to the above specimen and conditions; zero-point correction 0.001%.
17 117	Hertz, J., et al.	1972	L	84-448	NO562	Similar to the above specimen; panel B/EP-361-5; expansion for $[45^\circ]$ laminate in 0 deg direction; zero-point correction 0.004%.

TABLE 5-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18*	Hertz, J., Christian, J. L., and Varian, M.	1972	L	84-450	NO564	Similar to the above specimen; expansion for $[\pm 45^\circ]$ laminate in 45 deg direction; zero-point correction 0.005%.
19*	Hertz, J., et al.	1972	L	84-449	NO547	Similar to the above specimen and conditions; zero-point correction 0.004%.
20	Hertz, J., et al.	1972	L	79-447	NO582	Similar to the above specimen; expansion for $[0^\circ / \pm 45^\circ]$ laminate in 0 deg direction; zero-point correction 0.002%.
21	Hertz, J., et al.	1972	L	79-447	NO583	Similar to the above specimen and conditions; zero-point correction 0.002%.
22	Hertz, J., et al.	1972	L	83-452	NO584	Similar to the above specimen; expansion for $[0^\circ / \pm 45^\circ]$ in 90 deg direction; zero-point correction 0.007%.
23	Hertz, J., et al.	1972	L	83-452	NO585	Similar to the above specimen and conditions; zero-point correction 0.003%.

* Not shown in figure.

TABLE 5-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE
(Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$		
CURVE 1																	
293	0.000	339	0.018	78	-0.0502	366	0.138	78	-0.292	409	0.062	84	-0.068	131	-0.059		
307	0.005	366	0.029	130	-0.0429	407	0.215	131	-0.246	450	0.084	173	-0.047	213	-0.034		
309	0.006	406	0.047	172	-0.0355	448	0.287	173	-0.211			257	-0.016	299	0.005		
332	0.013	213	-0.0253	255	-0.0127			255	-0.156	CURVE 19*							
334	0.014	255	-0.0127			CURVE 12						298	0.010	334	0.023		
337	0.015	296	0.0020	76	-0.319	76	-0.319	298	0.010	CURVE 16						366	0.044
363	0.024	296	0.0043	131	-0.276	131	-0.276	339	0.103	84	-0.070	366	0.044	409	0.065		
365	0.025	338	0.0220	172	-0.214	172	-0.214	378	0.199	130	-0.060	449	0.091				
422	0.046	366	0.0373	214	-0.149	214	-0.149	410	0.296	173	-0.047						
425	0.048	407	0.0591	255	-0.071	255	-0.071	450	0.447	215	-0.032	CURVE 20					
426	0.048	450	0.0808	298	0.007	298	0.007			255	-0.014	79	-0.013	131	-0.017		
CURVE 2																	
293	0.000	78	-0.046	339	0.115	339	0.115	300	0.018	300	0.003	367	0.002	339	0.013		
309	0.036	131	-0.041	366	0.191	366	0.191	298	0.018	367	0.046	407	0.043	447	0.064		
309	0.036	172	-0.035	406	0.333	406	0.333	339	0.115	132	-0.061	CURVE 21					
310	0.038	214	-0.024	450	0.501	450	0.501	366	0.138	173	-0.049	79	-0.039	131	-0.032		
365	0.192	255	-0.011			CURVE 13						173	-0.029	215	-0.020		
365	0.192	296	0.002	76	-0.272	76	-0.272	296	-0.002	255	-0.020	255	-0.009	299	0.002		
366	0.195	337	0.020	129	-0.234	129	-0.234	337	0.035	338	0.107	339	0.013	367	0.023		
422	0.414	367	0.035	172	-0.184	172	-0.184	367	0.056	366	0.179	407	0.043	447	0.064		
422	0.414	408	0.079	211	-0.132	211	-0.132	408	0.079	449	0.094	CURVE 17					
422	0.414	450	0.079	255	-0.060	255	-0.060	450	0.418			84	-0.072	132	-0.061		
CURVE 3																	
293	0.000	82	-0.243	338	0.107	338	0.107	338	0.107	132	-0.061	131	-0.032	173	-0.029		
307	0.007	131	-0.217	366	0.179	366	0.179	366	0.179	173	-0.049	173	-0.029	215	-0.020		
309	0.008	173	-0.177	409	0.293	409	0.293	409	0.293	216	-0.038	255	-0.009	299	0.002		
310	0.008	214	-0.130	450	0.418	450	0.418	450	0.418	255	-0.020	339	0.013	367	0.023		
334	0.020	255	-0.070			CURVE 14						367	0.023	407	0.043		
335	0.020	299	0.068	78	-0.292	78	-0.292	299	0.068	300	0.003	CURVE 18*					
337	0.021	337	0.088	130	-0.238	130	-0.238	337	0.088	338	0.026	84	-0.070	130	-0.059		
363	0.034	366	0.138	174	-0.195	174	-0.195	367	0.038	367	0.038	175	-0.048	216	-0.035		
365	0.035	407	0.233	214	-0.133	214	-0.133	410	0.057	410	0.057	255	-0.017	299	0.005		
366	0.035	448	0.279	255	-0.074	255	-0.074	448	0.074	448	0.074	366	0.025	407	0.043		
CURVE 7																	
75	-0.045	82	-0.234	297	0.004	297	0.004	84	-0.070	84	-0.070	CURVE 22					
129	-0.040	131	-0.203	341	0.089	341	0.089	130	-0.059	130	-0.059	83	-0.164	131	-0.137		
171	-0.034	173	-0.160	368	0.147	368	0.147	175	-0.048	175	-0.048	174	-0.105				
213	-0.025	214	-0.119	409	0.259	409	0.259	216	-0.035	216	-0.035						
255	-0.013	255	-0.057	450	0.399	450	0.399	257	-0.017	257	-0.017						
298	0.002	299	0.008					299	0.005	299	0.005						
338	0.020	338	0.033					339	0.025	339	0.025						
366	0.033	366	0.056					407	0.043	407	0.043						
407	0.056	407	0.083					447	0.064	447	0.064						
CURVE 4																	
84	-0.043																
131	-0.038																
172	-0.032																
215	-0.025																
255	-0.013																
298	0.002																

* Not shown in figure.

TABLE 5-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF BORON FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$
<u>CURVE 22 (cont.)</u>	
215	-0.078
258	-0.040
299	0.006
338	0.042
368	0.069
410	0.103
452	0.123
<u>CURVE 23</u>	
83	-0.159
132	-0.135
174	-0.109
215	-0.078
255	-0.039
338	0.043
368	0.073
410	0.103
452	0.124

e. Thermal Diffusivity

There are no experimental data available for the thermal diffusivity of boron fiber epoxy composites. The calculation of the thermal diffusivity from the thermal conductivity, specific heat, and density values has not been carried out, because of the lack of uniformity in specimens for which other thermal properties are available. Furthermore, the thermal diffusivity of a composite is not a well-defined quantity.

3.6. Glass Fiber Epoxy Composite

The glass fiber epoxy composite consists usually of fine glass fibers surrounded by a matrix of epoxy resin. The other alternative form commonly used is the glass fabric reinforced plastics with epoxy surfacer.

Modified epoxy resins developed specifically for use in composites with glass fibers are available commercially. These are thermosetting resins used for low pressure laminating and normally cannot be used in continuous service above about 450 K, although intermittent service at a higher temperature up to 490 K is possible. Many of the various epoxy resins used as matrix constituents of composites are proprietary formulations, the exact chemical compositions of which are not available.

a. Thermal Conductivity

There are 93 sets of experimental data available for glass fibers and fabrics bonded by epoxy resins, mostly for temperatures ranging from about 100 K to somewhat above the softening temperature of about 450 K; one set of data (curve 30), not shown in the figure, is for a plate specimen measured at temperatures up to 1315 K.

The experimental data are tabulated in Table 6-3 and shown partially in Figure 6-1. The types of glass fibers and epoxy resins constituting the test specimens are:

YM-31-A glass/DER 332 (curves 1-8, 17-23),
 E-glass/NICC 1174/3 (curves 28, 29),
 E-glass/DER 332 (curves 13-16, 24-27, 30-32),
 E-glass/DEN 438 (curves 33-38),
 E-glass/ERSB-0111 (curves 40, 41),
 S-glass/DEN 438 (curves 42, 43),
 S-glass/E-787 (curves 44-67),
 S-glass/DER 332 (curves 68, 69),
 S-glass/DER 332/DEH 50 (curves 70-84), and
 S-glass/Polaris ((curves 90-93).

Further information on specimen characterization and measurement conditions is given in Table 6-2.

Since the thermal conductivity of these composites depends on the type of glass and resin, the relative amounts of each and the direction of heat flow, no single set of recommended or provisional values can be given. The typical values tabulated in Table

6-1 and shown in Figure 6-1 are presented for a 35% ERSB on epoxy resin reinforced by parallelly laminated E-glass 181 fabric, density 1.87 g cm^{-3} , for heat flow perpendicular to the fabric. These values are based primarily on the measurements of Lewis [128] (curves 40 and 41).

TABLE 6-1. TYPICAL THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITES

[Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹]

T	k
100	0.0027
150	0.0032
200	0.0036
250	0.0040
273.15	0.0041
293	0.0042
300	0.0043
350	0.0045
400	0.0046
450	0.0044

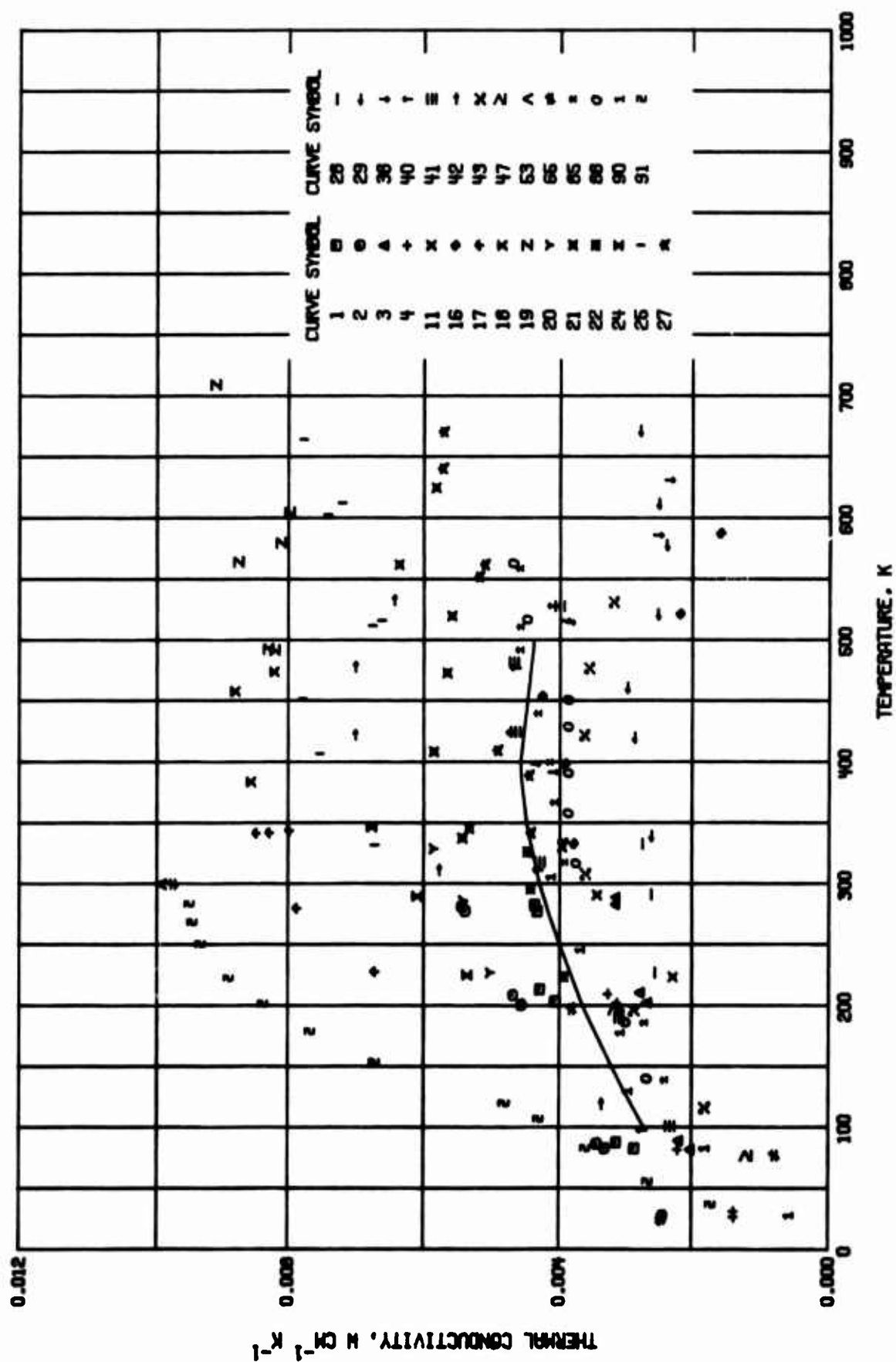


FIGURE 6-1. THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITES.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 120, 121	Campbell, M.D., Haskins, J.F., O'Barr, G.L., and Hertz, J.	1964	L	83-283	D	80 Owens-Corning high modulus YM-31-A glass fiber roving containing an HTS finish and 20 Dow Chemical DER-332 epoxy resin with the fibers undirectional and parallel; $7 \times 7 \times 0.5$ in.; heat flow parallel to fiber direction; measured in nitrogen atm.
2 120, 121	Campbell, M.D., et al.	1964	L	25-282	D	Same as the above specimen except measured in helium atm.
3 121, 122	Campbell, M.D., et al.	1963	L	82-289	D	Same as the above specimen except sawed into $7 \times 0.5 \times 0.5$ in. strips and reassembled with epoxy adhesive such that heat flow perpendicular to the fibers; measured in nitrogen atm.
4 121, 122	Campbell, M.D., et al.	1963	L	27-210	D	Same as the above specimen except measured in helium atm.
5* 120, 121	Campbell, M.D., et al.	1964	L	84-32	E	80 Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish and 20 Dow Chemical DER-332 epoxy resin cured with an acid anhydride; $7 \times 7 \times 0.5$ in.; alternate layers of the simulated helical filament-wound fiber roving cross-plied at angles of 57° and 303° from the horizontal axis; heat-flow parallel to the thickness with the fiber; measured in nitrogen atm.
6* 120, 121	Campbell, M.D., et al.	1964	L	26-282	E	Same as the above specimen except measured in helium atm.
7* 121, 122	Campbell, M.D., et al.	1963	L	83-281	E	Same as the above specimen except sawed into $7 \times 0.5 \times 0.5$ in. strips and reassembled with epoxy adhesive such that heat flow perpendicular to the thickness; measured in nitrogen atm.
8* 121, 122	Campbell, M.D., et al.	1963	L	26-285	E	Same as the above specimen except measured in helium atm.
9* 58	Careaga, J.A., Mayer, E.R., and Del Castillo, L.	1970	L	81-216		No details reported.
10* 123	Baltakis, F.P., Hurd, D.E., and Holmes, R.F.	1960	L	298	A2(XSP-2A-1)	35% epoxy resin reinforced by 15% glass fiber and filled by 50% ceramic; $1 \times 1 \times 0.125$ in.; density 2.110 g cm^{-3} ; reported error 3-5%.
11 124	Engelke, W.T., Pears, C.D., and Ogelsby, S., Jr.	1963	L	224-330	d-1	30% NRC 1174/3 epoxy resin reinforced by 70% randomly oriented Owens-Corning "E" glass flakes $2 \mu\text{m}$ thick and 200 to 2000 μm in diameter; 0.2339 in. thick plate specimen; supplied by Narmco Research and Development; molded under 10 psi at 450 K for 3 min; cured under 800 psi at 450 K for 2 hr; density 1.97 g cm^{-3} .
12* 124	Engelke, W.T., et al.	1963	L	223-332	d-2	25% NRC 1174/3 epoxy resin reinforced by 75% Owens-Corning "E" glass flakes $2 \mu\text{m}$ thick and 200 to 2000 μm in diameter; 0.2408 in. thick plate specimen; supplied by Narmco Research and Development; cured under 1500 psi at 450 K for 2 hr; density 1.97 g cm^{-3} .
13* 125, 126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1963	L	222-334	c-2	30% Dow Chemical DER 332 epoxy resin reinforced by 70% "E" glass fiber roving in 40 layers of parallel orientation; 0.2404 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 394 K for 2 hr; density 1.95 g cm^{-3} .
14* 125, 126	Pears, C.D., et al.	1963	L	349-615	c-2	Same as the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
15*	125, 126	Pears, C. D., Engelke, W. T., and Thornburgh, J. D.	1963	L	225-332	d-1	The specimen for curve No. 11 remeasured.
16	125, 126	Pears, C. D., et al.	1963	L	334-588	d-1	Same as the above specimen.
17	125, 126	Pears, C. D., et al.	1963	L	228-344	c-1	40% Dow Chemical DER 332 epoxy resin reinforced by 60% unidirectional parallel high modulus YM 31 A glass fiber roving with HTS finish; 0.2213 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.91 g cm ⁻³ ; heat flow parallel to reinforcement glass roving in a-direction.
18	125, 126	Pears, C. D., et al.	1963	L	384-474	c-1	Same as the above specimen.
19	125, 126	Pears, C. D., et al.	1963	L	492-710	c-1	Same as the above specimen.
20	125, 126	Pears, C. D., et al.	1963	L	227-329	c-1	Similar to the above specimen except thickness 0.2365 in.; heat flow perpendicular to reinforcement glass roving in b-direction.
21	125, 126	Pears, C. D., et al.	1963	L	338-672	c-1	Same as the above specimen.
22	125, 126	Pears, C. D., et al.	1963	L	224-332	c-1	Similar to the above specimen except thickness 0.2491 in.; heat flow in the thickness of the specimen in c-direction.
23*	125, 126	Pears, C. D., et al.	1963	L	335-609	c-1	Same as the above specimen.
24	125, 126	Pears, C. D., et al.	1963	L	226-347	c-2	30% Dow Chemical DER 332 epoxy resin reinforced by 70% parallel "E" glass fiber roving with HTS finish in 40 layers; 0.2412 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.85 g cm ⁻³ ; heat flow parallel to reinforcement roving in a-direction.
25	125, 126	Pears, C. D., et al.	1963	L	332-665	c-2	Same as the above specimen.
26*	125, 126	Pears, C. D., et al.	1963	L	229-324	c-2	Similar to the above specimen except thickness 0.2042 in.; heat flow perpendicular to reinforcement roving in b-direction.
27	125, 126	Pears, C. D., et al.	1963	L	342-671	c-2	Same as the above specimen.
28	125, 126	Pears, C. D., et al.	1963	L	227-333	c-3	40% Dow Chemical DER 332 epoxy resin reinforced by 60% high modulus YM 31 A glass fiber roving with HTS finish in 40 layers cross plied parallel to and 66° from horizontal axis; 0.2302 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 1.94 g cm ⁻³ ; heat flow through thickness of the specimen in c-direction.
29	125, 126	Pears, C. D., et al.	1963	L	339-672	c-3	Same as the above specimen.
30*	125, 126	Pears, C. D., et al.	1963	L	225-332	c-4	20% Dow Chemical DER 332 epoxy resin reinforced by 80% "E" glass fiber roving with HTS finish in 40 cross plied layers; 0.2702 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 2.10 g cm ⁻³ ; heat flow through thickness of specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
31* 125, 126	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1963	L	356-479	c-4	Same as the above specimen.
32* 125, 126	Pears, C.D., et al.	1963	L	336-624	c-4	Same as the above specimen.
33* 125, 126	Pears, C.D., et al.	1963	L	229-333	c-5	20% Dow Chemical DEN 438 epoxy resin reinforced by 80% "E" glass fiber roving 20 ends with HTS finish in 40 unidirectional parallel layers; 0.2466 in. thick plate specimen; cured under 200 psi at 367 K for 2 hr and at 393 K for 2 hr; density 2.06 g cm ⁻³ ; heat flow through thickness of specimen in c-direction.
34* 125, 126	Pears, C.D., et al.	1963	L	338-674	c-5	Same as the above specimen.
35* 125, 126	Pears, C.D., et al.	1963	L	221-332	d-1	Similar to the specimen for curve No. 11 except thickness 0.2107 in.; heat flow parallel to the flake orientation.
36* 125, 126	Pears, C.D., et al.	1963	L	340-616	d-1	Same as the above specimen.
37* 125, 126	Pears, C.D., et al.	1963	L	223-333	d-2	Similar to the specimen for curve No. 12 except thickness 0.2406 in.; heat flow through thickness of specimen in c-direction.
38 125, 126	Pears, C.D., et al.	1963	L	336-631	d-2	Same as the above specimen.
39* 127	Gray, C.O.	1958	L	396-1315		Fiberglass monofilament roving bonded with 23% epoxy resin; plate specimen supplied by Goodyear Aircraft Corp.; density 1.90 g cm ⁻³ ; data taken from smooth curve.
40 128	Lewis, W.	1965	C	98-528	EP-E	36.0% ERSB-0111 epoxy resin reinforced by parallelly laminated "E" glass 181 fabric; 2.5 x 2.5 x 0.201 in.; density 1.92 g cm ⁻³ ; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
41 128	Lewis, W.	1955	C	101-528	EP-S	35.0% ERSB-0111 epoxy resin reinforced by parallelly laminated "E" glass 181 fabric; 2.5 x 2.5 x 0.231 in.; density 1.82 g cm ⁻³ ; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
42 128	Lewis, W.	1965	C	119-533	DEN-S-R	19.3% Dow Chemical DEN 438 epoxy Novalac resin reinforced by parallelly laminated "S" glass 181 fabric; 2.5 x 2.5 x 0.245 in.; density 1.99 g cm ⁻³ ; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
43 128	Lewis, W.	1965	C	116-531	DEN-S-L	32.0% Dow Chemical DEN 438 epoxy Novalac resin reinforced by parallelly laminated "S" glass 181 fabric; 2.5 x 2.5 x 0.277 in.; density 1.65 g cm ⁻³ ; heat flow perpendicular to fabric; Inconel 702 and pyroceram used as comparative materials.
44* 129, 130	Toth, L.W., Boller, T.J., Butcher, I.R., Karlotis, A.H., and Yoder, F.D.	1965	L	77-300	BFW-7A7B-23-1	E-787 epoxy resin reinforced by cross-ply "S" glass 901 roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
45* 129, 130	Toth, L.W., et al.	1965	L	20-300	BFW-7A7B-23-2	Similar to the above specimen.
46* 129, 130	Toth, L.W., et al.	1965	L	77-300	BFW-7A7B-23-3	Similar to the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
47 129, 130	Toth, L. W., Boller, T. J., Butcher, I. R., Karlotis, A. H., and Yoder, F. D.	1965	L	77-300	UFW-9A9B-23-1	E-787 epoxy resin reinforced by unidirectional "S" glass 901 roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
48* 130	Toth, L. W., et al.	1966	L	20-300	UFW-9A9B-23-2	Similar to the above specimen.
49* 130	Toth, L. W., et al.	1966	L	77-300	UFW-9A9B-23-3	Similar to the above specimen.
50* 129, 130	Toth, L. W., et al.	1965	L	77-300	1543-10A-23-1	E-787 epoxy resin reinforced by "S" glass 1543 cloth laminates; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
51* 129, 130	Toth, L. W., et al.	1966	L	20-300	1543-10A-23-2	Similar to the above specimen.
52* 129, 130	Toth, L. W., et al.	1966	L	77-300	1543-10A-23-3	Similar to the above specimen.
53 129, 130	Toth, L. W., et al.	1965	L	77-300	1581-9A9B-23-1	E-787 epoxy resin reinforced by "S" glass 1581 cloth laminates; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
54* 130	Toth, L. W., et al.	1966	L	20-300	1581-9A9B-23-2	Similar to the above specimen.
55* 130	Toth, L. W., et al.	1966	L	77-300	1581-9A9B-23-3	Similar to the above specimen.
56* 129, 130	Toth, L. W., et al.	1965	L	77-300	BFW-7A7B-31-1	Similar to the specimen for curve No. 44 except heat flow perpendicular to reinforcement.
57* 129, 130	Toth, L. W., et al.	1965	L	20-300	BFW-7A7B-31-2	Similar to the above specimen.
58* 130	Toth, L. W., et al.	1966	L	77-300	BFW-7A7B-31-3	Similar to the above specimen.
59* 130	Toth, L. W., et al.	1966	L	77-300	UFW-9A9B-31-1	Similar to the specimen for curve No. 47 except heat flow perpendicular to reinforcement.
60* 130	Toth, L. W., et al.	1966	L	20-300	UFW-9A9B-31-2	Similar to the above specimen.
61* 130	Toth, L. W., et al.	1966	L	77-300	UFW-9A9B-31-3	Similar to the above specimen.
62* 129, 130	Toth, L. W., et al.	1965	L	77-300	1543-10A-31-1	Similar to the specimen for curve No. 50 except heat flow perpendicular to reinforcement.
63* 130	Toth, L. W., et al.	1966	L	20-300	1543-10A-31-2	Similar to the above specimen.
64* 130	Toth, L. W., et al.	1966	L	77-300	1543-10A-31-3	Similar to the above specimen.
65 129, 130	Toth, L. W., et al.	1965	L	77-300	1581-9A9B-31-1	Similar to the specimen for curve No. 53 except heat flow perpendicular to reinforcement.
66* 130	Toth, L. W., et al.	1966	L	20-300	1581-9A9B-31-2	Similar to the above specimen.
67* 130	Toth, L. W., et al.	1966	L	77-300	1581-9A9B-31-3	Similar to the above specimen.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
68* 130	Toth, L. W., Boller, T. J., Butcher, I. R., Karotis, A. H., and Yoder, F. D.	1966	L	77, 300	2006-4-1	DER 332/BF ₃ epoxy resin reinforced by cross-piled "S" glass roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
69* 130	Toth, L. W., et al.	1966	L	77, 300	2006-5-1	Similar to the above specimen except heat flow perpendicular to reinforcement.
70* 130	Toth, L. W., et al.	1966	L	77, 300	3006-4-1	DER 332/DEH 50 epoxy resin reinforced by cross-piled "S" glass roving; 0.25 in. diameter x 3 in. long; heat flow parallel to reinforcement.
71* 130	Toth, L. W., et al.	1966	L	77, 300	3006-5-1	Similar to the above specimen except heat flow perpendicular to reinforcement.
72* 126	Pears, C. D., Engellke, W. T., and Thornburgh, J. D.	1964	L	231-328	c-3	Similar to the specimen for curve No. 28; heat flow in a-direction.
73* 126	Pears, C. D., et al.	1964	L	333-650	c-3	Same as the above specimen.
74* 126	Pears, C. D., et al.	1964	L	225-324	c-3	Similar to the above specimen except heat flow in b-direction.
75* 126	Pears, C. D., et al.	1964	L	329-702	c-3	Same as the above specimen.
76* 126	Pears, C. D., et al.	1964	L	223-326	c-4	Similar to the specimen for curve No. 30; heat flow in a-direction.
77* 126	Pears, C. D., et al.	1964	L	330-664	c-4	Same as the above specimen.
78* 126	Pears, C. D., et al.	1964	L	220-326	c-4	Similar to the above specimen except heat flow in b-direction.
79* 126	Pears, C. D., et al.	1964	L	358-655	c-4	Same as the above specimen.
80* 126	Pears, C. D., et al.	1964	L	234-328	c-5	Similar to the specimen for curve No. 33; heat flow in a-direction.
81* 126	Pears, C. D., et al.	1964	L	319-676	c-5	Same as the above specimen.
82* 126	Pears, C. D., et al.	1964	L	229-321	d-2	Similar to the specimen for curve No. 37; heat flow parallel to reinforcement.
83* 126	Pears, C. D., et al.	1964	L	294-609	d-2	Same as the above specimen.
84* 126	Pears, C. D., et al.	1964	L	325-674	d-2	Same as the above specimen.
85 131	Avco Corporation	1966	L	139-559		Same as the above specimen.
86* 131	Avco Corporation	1966	L	142-573		36 to 45% U.S. Polymeric epoxy novolac NMA resin reinforced by glass fabric 181; density 1.775 g cm ⁻³ ; heat flow perpendicular to reinforcing laminations.
87* 131	Avco Corporation	1966	L	138-578		Similar to the above specimen except density 1.828 g cm ⁻³ .
88 131	Avco Corporation	1966	L	141-564		Similar to the above specimen except density 1.829 g cm ⁻³ .
89* 131	Avco Corporation	1966	L	319-451		Similar to the above specimen except heat flow parallel to reinforcing laminations and density 1.772 g cm ⁻³ .
90 116	Gille, J. P.	1969	L	28-306	1	Similar to the above specimen.
91 116	Gille, J. P.	1969	L	37-284	2	81.3 "S" glass fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.002 in. I.D., 1.140 in. O.D., and 0.503 in. in effective length; density 2.02 g cm ⁻³ ; heat flow perpendicular to fibers; data taken from smooth curve.
92* 116	Gille, J. P.	1969	L	56, 279	3	79.4 "S" glass fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.000 in. I.D., 1.132 in. O.D., and 0.500 in. in effective length; density 2.02 g cm ⁻³ ; heat flow parallel to fibers; data taken from smooth curve.

* Not shown in figure.

TABLE 6-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
93* 132	Ogawa, K. and Noguchi, Y.	1968	P	300-422	LE-61N	95 x 65 x 0.99 mm; density 1.76 g cm^{-3} ; thermal conductivity values calculated from thermal diffusivity and specific heat measured by infrared radiation method.

* Not shown in figure.

[illegible]

* Not shown in figure.

TABLE 6-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

T	k	T	k	T	k	T	k	T	k
CURVE 34 (cont.)*		CURVE 39 (cont.)		CURVE 45 (cont.)*		CURVE 53		CURVE 61*	
499.6	0.00534	1086	0.0226	77	0.00109	77	0.00100	77	0.00130
574.2	0.00524	1315	0.0225	197	0.00320	197	0.00314	197	0.00330
610.5	0.00499			300	0.00857	300	0.00994	300	0.00780
673.7	0.00470	CURVE 40				CURVE 54*		CURVE 62*	
CURVE 35*		97.8	0.00274	CURVE 46*		CURVE 55*		CURVE 63*	
221.1	0.00436	200	0.00374	77	0.00090	20	0.00086	20	0.00105
290.0	0.00538	311	0.00433	197	0.00201	77	0.00100	77	0.00090
332.1	0.00551	424	0.00473	300	0.00640	197	0.00300	197	0.00372
CURVE 36*		477	0.00467			300	0.00853	300	0.01100
340.2	0.00598	528	0.00412	CURVE 47		CURVE 56*		CURVE 64*	
388.6	0.00622	CURVE 41		77	0.00116	77	0.00092	77	0.00113
453.8	0.00692	101	0.00232	197	0.00312	197	0.00292	197	0.00215
503.4	0.00702	190	0.00309	300	0.00893	300	0.01050	300	0.01015
562.2	0.00689	318	0.00430	CURVE 48*		CURVE 57*		CURVE 65	
615.8	0.00558	425	0.00467	20	0.00115	20	0.00108	77	0.00079
CURVE 37*		482	0.00469	77	0.00127	77	0.00107	197	0.00382
222.9	0.00346	528	0.00401	197	0.00211	197	0.00317	300	0.00977
286.5	0.00402	CURVE 42		300	0.00666	300	0.01080	CURVE 66*	
332.6	0.00410	119	0.00336	CURVE 49*		CURVE 58*		CURVE 67*	
CURVE 38		201	0.00456	77	0.00133	77	0.00127	20	0.00117
335.6	0.00395	311	0.00578	197	0.00253	197	0.00337	77	0.00120
391.8	0.00410	422	0.00701	300	0.00669	300	0.01055	197	0.00375
396.3	0.00437	478	0.00700	CURVE 50*		CURVE 59*		300	0.00880
514.3	0.00385	533	0.00643	77	0.00084	20	0.00080	CURVE 68*	
515.7	0.00391	CURVE 43		197	0.00268	77	0.00100	77	0.00136
585.8	0.00251	116	0.00182	300	0.00795	197	0.00240	197	0.00272
631.1	0.00234	196	0.00286	CURVE 51*		300	0.00650	300	0.00778
CURVE 39*		308	0.00361	20	0.00108	CURVE 52*		CURVE 69*	
336.6	0.00393	422	0.00363	77	0.00080	77	0.00135	77	0.00107
391.8	0.00410	477	0.00356	197	0.00240	197	0.00360	300	0.00650
396.3	0.00437	531	0.00319	300	0.00650	300	0.00679	CURVE 70*	
514.3	0.00385	CURVE 44*		CURVE 52*		CURVE 60*		CURVE 71*	
515.7	0.00391	77	0.00108	77	0.00080	20	0.00119	77	0.00110
585.8	0.00251	197	0.00347	197	0.00240	77	0.00132	300	0.00620
631.1	0.00234	300	0.00755	300	0.00629	197	0.00299	CURVE 72*	
CURVE 39*		CURVE 45*		20	0.00075	300	0.00679	231	0.00337
336.6	0.00393	20	0.00075	CURVE 45*		CURVE 60*		299	0.00505
391.8	0.00410	77	0.00123	77	0.00123	20	0.00119	328	0.00495
396.3	0.00437	197	0.00220	197	0.00220	77	0.00132	CURVE 73*	
514.3	0.00385	300	0.00629	300	0.00629	197	0.00299	333	0.00502
515.7	0.00391	CURVE 46*		CURVE 46*		CURVE 60*		381	0.00509
585.8	0.00251	77	0.00108	77	0.00108	20	0.00117	450	0.00557
631.1	0.00234	197	0.00347	197	0.00240	77	0.00127	497	0.00570
CURVE 39*		300	0.00755	300	0.00650	197	0.00337	579	0.00567
336.6	0.00393	CURVE 47*		CURVE 47*		300	0.01055	614	0.00567
391.8	0.00410	77	0.00108	77	0.00108	CURVE 59*		650	0.00541
396.3	0.00437	197	0.00347	197	0.00240	CURVE 67*		CURVE 74*	
514.3	0.00385	300	0.00755	300	0.00650	20	0.00117	225	0.00412
515.7	0.00391	CURVE 48*		CURVE 48*		77	0.00120	324	0.00487
585.8	0.00251	77	0.00108	77	0.00108	197	0.00375	CURVE 75*	
631.1	0.00234	300	0.00755	300	0.00650	300	0.00880	329	0.00482
CURVE 39*		CURVE 49*		CURVE 49*		CURVE 67*		353	0.00476
336.6	0.00393	77	0.00108	77	0.00108	77	0.00135	411	0.00489
391.8	0.00410	197	0.00347	197	0.00240	197	0.00360	468	0.00584
396.3	0.00437	300	0.00755	300	0.00650	300	0.00690	503	0.00567
514.3	0.00385	CURVE 50*		CURVE 50*		CURVE 68*		561	0.00557
515.7	0.00391	77	0.00108	77	0.00108	77	0.00136	579	0.00513
585.8	0.00251	197	0.00347	197	0.00240	197	0.00375	611	0.00535
631.1	0.00234	300	0.00755	300	0.00650	300	0.00880	702	0.00541
CURVE 39*		CURVE 51*		CURVE 51*		CURVE 69*		CURVE 76*	
336.6	0.00393	77	0.00108	77	0.00108	20	0.00119	CURVE 77*	
391.8	0.00410	197	0.00347	197	0.00240	77	0.00132	CURVE 78*	
396.3	0.00437	300	0.00755	300	0.00650	197	0.00299	CURVE 79*	
514.3	0.00385	CURVE 52*		CURVE 52*		CURVE 70*		CURVE 80*	
515.7	0.00391	77	0.00108	77	0.00108	20	0.00119	CURVE 81*	
585.8	0.00251	197	0.00347	197	0.00240	77	0.00132	CURVE 82*	
631.1	0.00234	300	0.00755	300	0.00650	197	0.00299	CURVE 83*	
CURVE 39*		CURVE 53*		CURVE 53*		CURVE 71*		CURVE 84*	
336.6	0.00393	77	0.00108	77	0.00108	20	0.00119	CURVE 85*	
391.8	0.00410	197	0.00347	197	0.00240	77	0.00132	CURVE 86*	
396.3	0.00437	300	0.00755	300	0.00650	197	0.00299	CURVE 87*	
514.3	0.00385	CURVE 54*		CURVE 54*		CURVE 72*		CURVE 88*	
515.7	0.00391	77	0.00108	77	0.00108	20	0.00119	CURVE 89*	
585.8	0.00251	197	0.00347	197	0.00240	77	0.00132	CURVE 90*	
631.1	0.00234	300	0.00755	300	0.00650	197	0.00299	CURVE 91*	
CURVE 39*		CURVE 55*		CURVE 55*		CURVE 73*		CURVE 92*	
336.6	0.00393	77	0.00108	77	0.00108	20	0.00119	CURVE 93*	
391.8	0.00410	197	0.00347	197	0.00240	77	0.00132	CURVE 94*	
396.3	0.00437	300	0.00755	300	0.00650	197	0.00299	CURVE 95*	
514.3	0.00385	CURVE 56*		CURVE 56*		CURVE 74*		CURVE 96*	
515.7	0.00391	77	0.00108	77	0.00108	20	0.00119	CURVE 97*	
585.8	0.00251	197	0.00347	197	0.00240	77	0.00132	CURVE 98*	
631.1	0.00234	300	0.00755	300	0.00650	197	0.00299	CURVE 99*	

* Not shown in figure.

TABLE 6-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GLASS FIBER EPOXY COMPOSITE (continued)

T	k	T	k	T	k	T	k
<u>CURVE 76*</u>		<u>CURVE 82 (cont.)*</u>		<u>CURVE 87 (cont.)*</u>		<u>CURVE 92*</u>	
223	0.00437	292	0.00617	485	0.00379	56	0.00299
290	0.00568	321	0.00588	539	0.00427	279	0.00928
326	0.00588			578	0.00447		
<u>CURVE 77*</u>		<u>CURVE 83*</u>		<u>CURVE 88</u>		<u>CURVE 93*</u>	
330	0.00567	294	0.00562	141	0.00267	300	0.00325
393	0.00570	332	0.00596	187	0.00299	334	0.00342
443	0.00665	457	0.00596	318	0.00376	377	0.00320
469	0.00650	609	0.00637	359	0.00388	422	0.00325
499	0.00652			392	0.00388		
559	0.00678	<u>CURVE 84*</u>		430	0.00388		
621	0.00613	325	0.00607	452	0.00388		
643	0.00588	392	0.00614	518	0.00450		
664	0.00606	478	0.00640	564	0.00471		
<u>CURVE 78*</u>		526	0.00656				
220	0.00449	581	0.00659	<u>CURVE 89*</u>			
291	0.00547	674	0.00609	319	0.00377		
326	0.00586			358	0.00389		
<u>CURVE 79*</u>		<u>CURVE 85</u>		392	0.00388		
358	0.00545	139	0.00239	430	0.00388		
489	0.00603	186	0.00270	451	0.00388		
533	0.00622	318	0.00393	<u>CURVE 90</u>			
655	0.00570	367	0.00408	28	0.000588		
<u>CURVE 80*</u>		400	0.00415	83	0.00182		
234	0.00453	440	0.00433	130	0.00296		
293	0.00490	492	0.00460	178	0.00308		
328	0.00560	511	0.00459	246	0.00369		
<u>CURVE 81*</u>		559	0.00460	306	0.00414		
319	0.00599	<u>CURVE 86*</u>		<u>CURVE 91</u>			
352	0.00586	142	0.00279	37	0.00173		
378	0.00586	193	0.00329	56	0.00265		
441	0.00619	339	0.00414	83	0.00360		
509	0.00637	381	0.00436	107	0.00431		
568	0.00637	433	0.00466	120	0.00483		
609	0.00623	485	0.00474	154	0.00672		
676	0.00616	538	0.00474	179	0.00767		
<u>CURVE 82*</u>		573	0.00495	202	0.00838		
229	0.00558	<u>CURVE 87*</u>		223	0.00891		
		136	0.00261	251	0.00935		
		192	0.00312	269	0.00948		
		343	0.00367	284	0.00952		
		365	0.00357				
		434	0.00353				

* Not shown in figure.

b. Specific Heat

There are 38 sets of experimental data available for the specific heat of glass fiber epoxy composites. The information on the specimen characterization and measurement conditions for each of the data sets is given in Table 6-5. The experimental data are tabulated in Table 6-6 and partially shown in Figures 6-2A through 6-2D. These data sets cover the following types of composites:

- E-glass fibers/Narmco (curves 1-7, 37, 38),
- E-glass fibers/Dupont P.I. (curve 8),
- YM-31-A glass fibers/DER 332 (curves 10, 13, 26, 27, 32, 34),
- "181" glass fabric/shell X-131 (curves 22, 23),
- Glass fibers/Epon 828 (curves 11, 28-30),
- E-glass fibers/DER 332 (curves 33, 35), and
- Glass fibers/DEN 438 (curves 24, 25, 36).

The provisional values generated as discussed in the following sections are for well cured and thermally stable composites. The resin content of each composite is given together with the specific heat values.

E-Glass/DER 332 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2A are based on the measurements of Pears, Engelke, and Thornburgh [126] (curves 33 and 35). These values are considered accurate to about $\pm 10\%$. This composite begins to degrade near 550 K.

E-Glass/DEN 438 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2B are based on the measurements of Pears, Engelke, and Thornburgh [126] (curve 36). These values are considered accurate to about $\pm 10\%$. The investigations of Lagedrost et al. [133] (curves 24 and 25) yield considerably higher values for their composites containing chopped glass and microballoons.

E-Glass/Narmco Epoxy Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2C are based on the measurements of Kim [118] (curves 1-7). These values are considered accurate to within $\pm 10\%$. The specific heat values of Pears et al. [126] (curves 37 and 38) for

composites with Narmco NRC 1174/3 epoxy resin (molded from powder) are considerably higher below 350 K and lower above that temperature.

YM-31-A Glass/DER 332 Composites

The provisional values tabulated in Table 6-4 and shown in Figure 6-2D are based primarily on the data of Campbell et al. [134] (curve 26). The uncertainty of these values is about $\pm 10\%$. The specific heat values of Pears et al. [126] (curves 32 and 34) for composite containing 40 percent epoxy vary as much as 25% from the provisional values.

TABLE 6-4. PROVISIONAL SPECIFIC HEAT OF GLASS
FIBER EPOXY COMPOSITES

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	E-Glass Fibers					YM-31-A Glass Fibers
	DER-332 Epoxy	DEN-438 Epoxy	Narmco Epoxy			DER-332 Epoxy
	20 percent	20 percent	25 percent	38 percent	58 percent	20 percent
25						0.007
30						0.013
40						0.024
50						0.034
60						0.044
70						0.052
80						0.061
90						0.070
100						0.078
150						0.116
200	0.135	0.135				0.153
250	0.165	0.165				0.188
273.15	0.178	0.178				0.204
293	0.189	0.189				0.217
300	0.193	0.193	0.200	0.220	0.230	0.223
350	0.220	0.220	0.234	0.260	0.313	0.258
400	0.246	0.246	0.267	0.302	0.396	0.292
450	0.271	0.271				0.324
500	0.295	0.295				

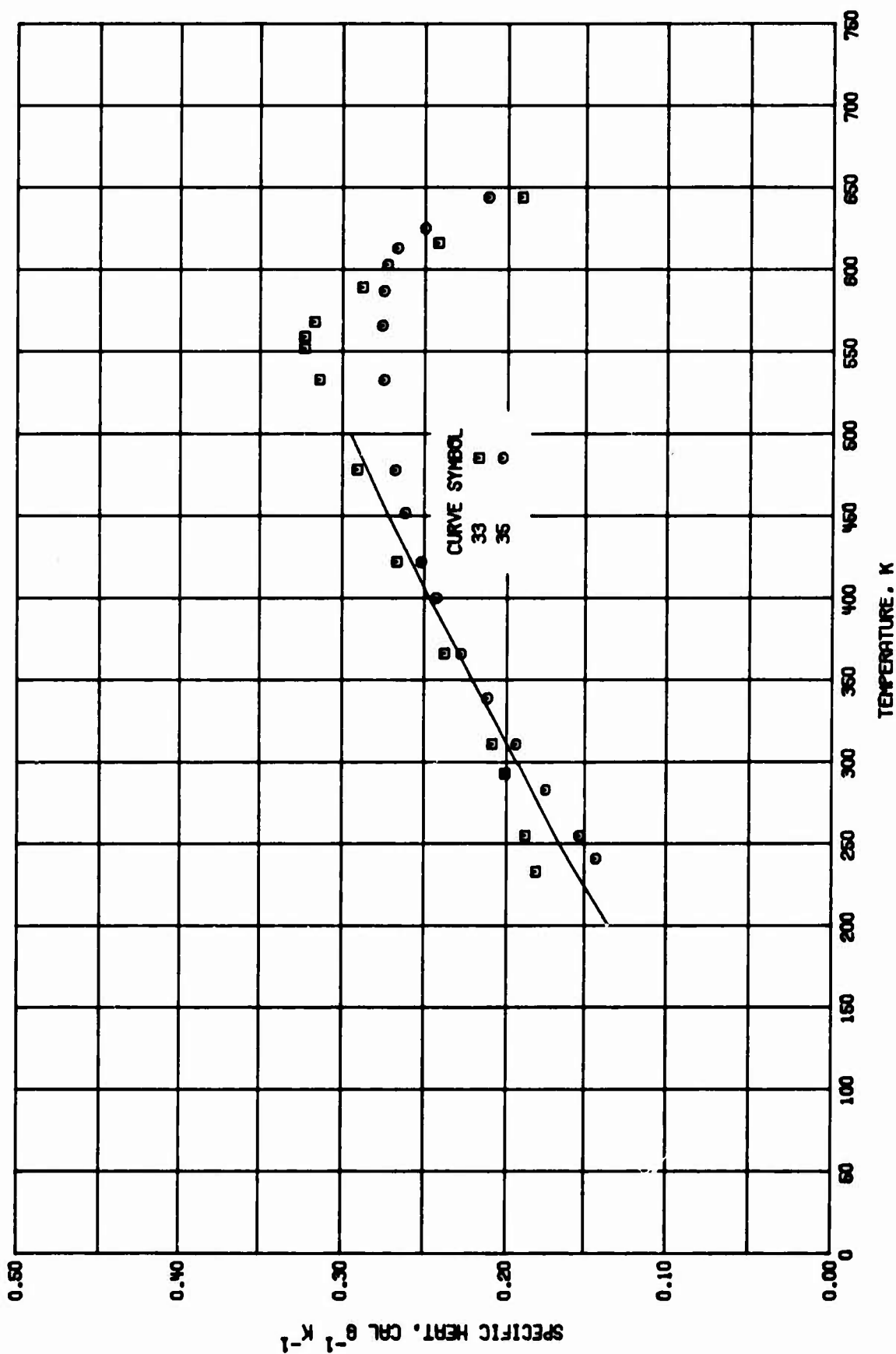


FIGURE 6-2A. SPECIFIC HEAT OF E-GLASS FIBER DER 332 EPOXY COMPOSITES .

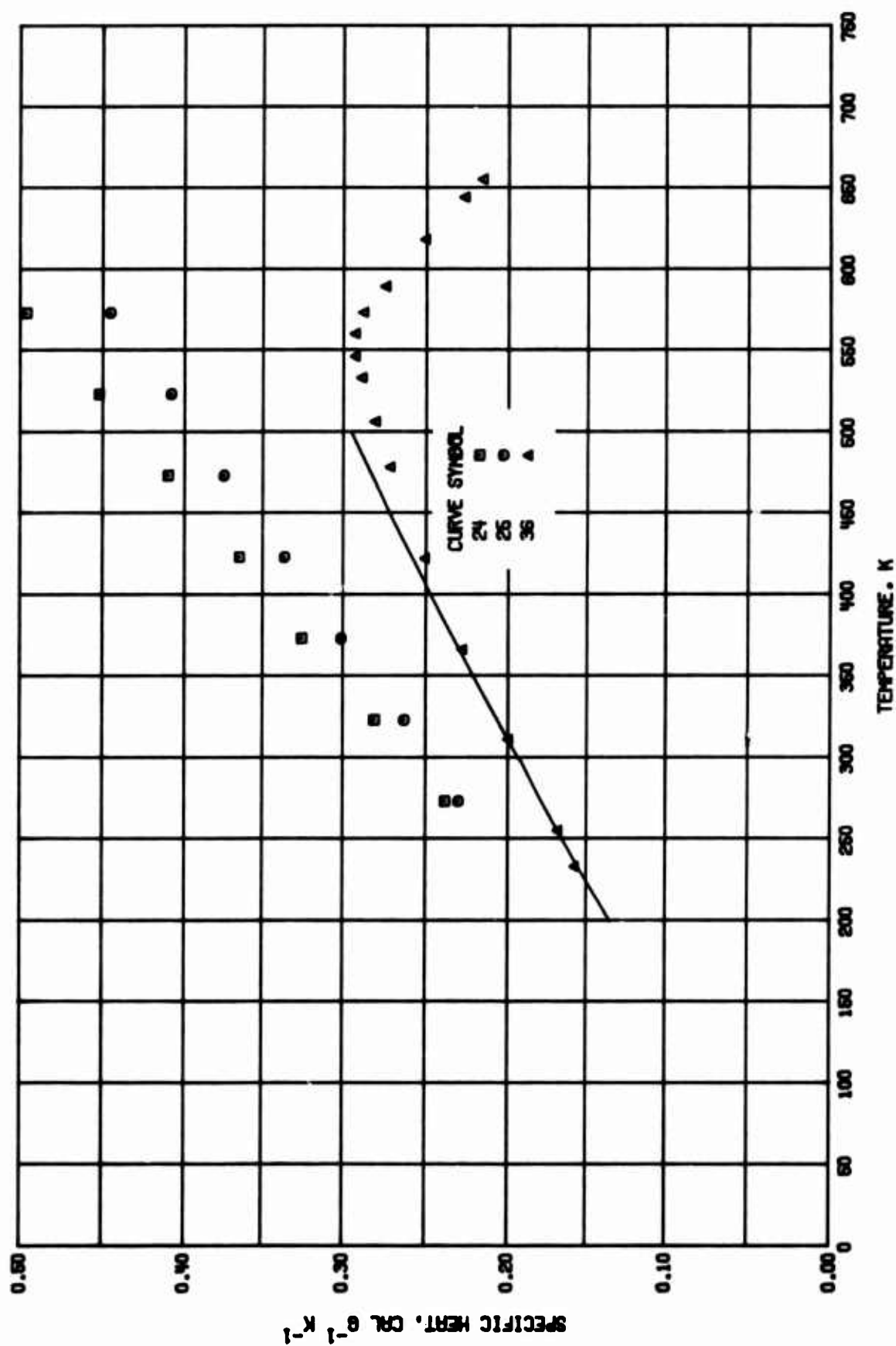


FIGURE 6-28. SPECIFIC HEAT OF E-GLASS FIBER DEN 436 EPOXY COMPOSITES.

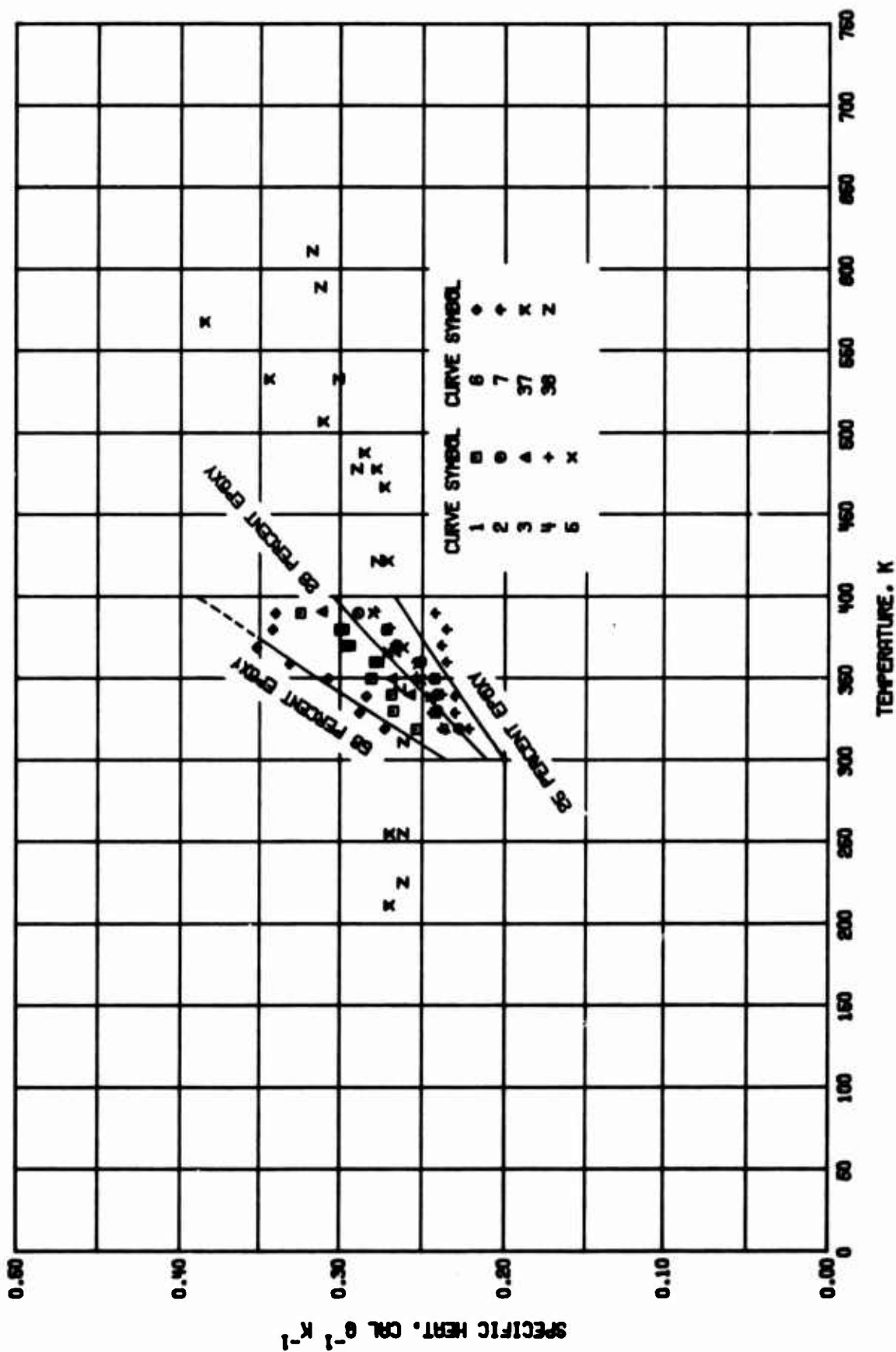


FIGURE 8-2C. SPECIFIC HEAT OF E-GLASS FIBER NARANCO EPOXY COMPOSITES .

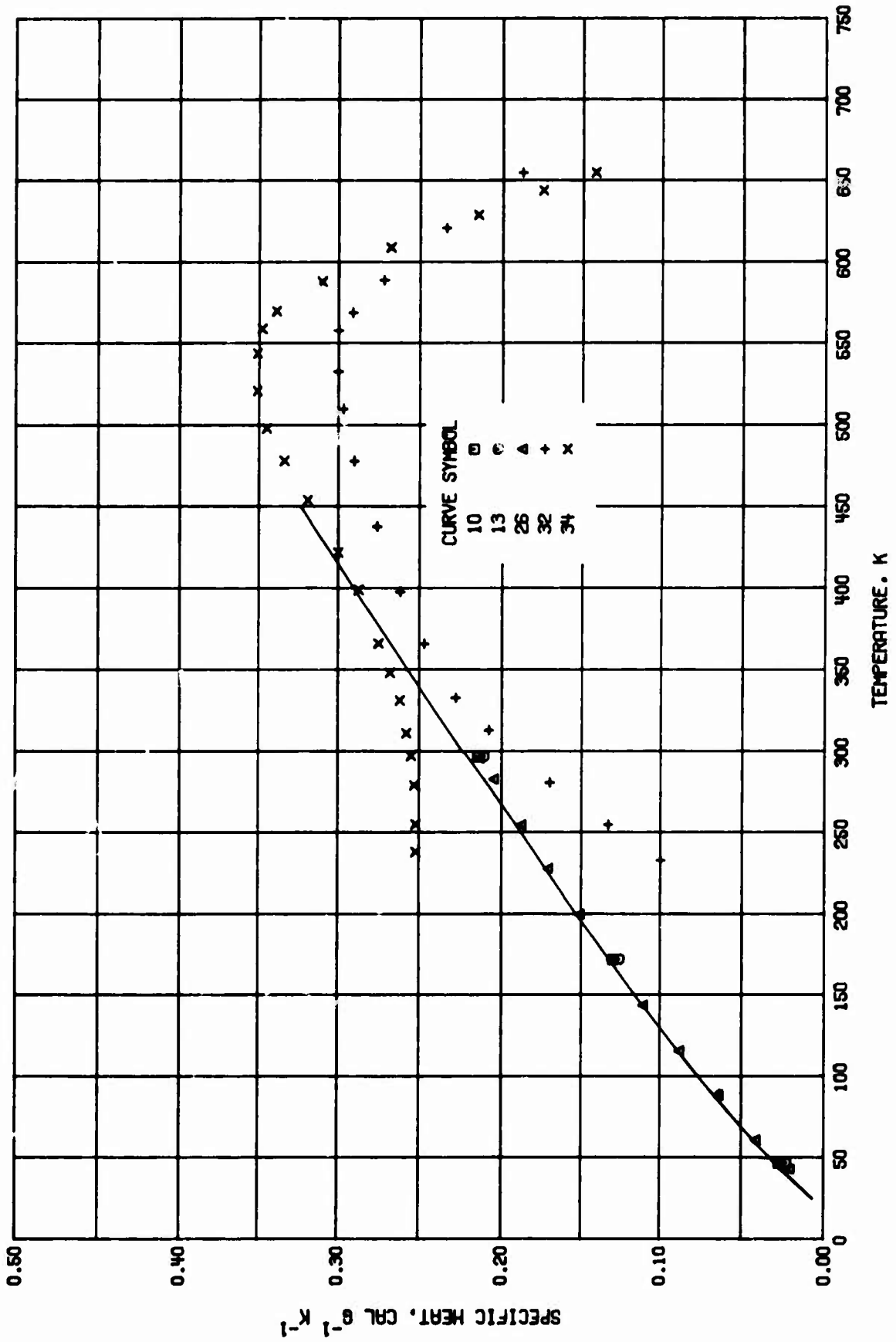


FIGURE 6-20. SPECIFIC HEAT OF YH-31-A GLASS FIBER DER 332 EPOXY COMPOSITES .

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 1	Composite laminate consisted of Narmco epoxy and E-glass 120 fibers; resin content 46.6 weight % after cure; density 1.748 g cm ⁻³ ; thickness 0.50 in.
2 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 2	Composite laminate consisted of Narmco epoxy and E-glass 143 fibers; resin content 37.7 weight % after cure; density 1.868 g cm ⁻³ ; thickness 0.50 in.
3 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 3	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 38.6 weight % after cure; density 1.868 g cm ⁻³ ; thickness 0.52 in.
4 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 4	Composite laminate consisted of Narmco epoxy and E-glass 182 fibers; resin content 38 weight % after cure; density 1.924 g cm ⁻³ ; thickness 0.75 in.
5 118	Kim, D. H.	1972	DSC	320-390	Specimen No. 6	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 30 weight % (52.2 volume %) after cure; density 2.004 g cm ⁻³ ; thickness 0.62 in.
6 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 8	Composite laminate consisted of Narmco epoxy and E-glass 181 fibers; resin content 57.6 weight % (90.5 volume %) after cure; density 1.603 g cm ⁻³ ; thickness 0.43 in.
7 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 9	Composite laminate consisted of Narmco high-temperature cure epoxy and E-glass 181 fibers; resin content 26.3 weight % after cure; density 1.900 g cm ⁻³ ; thickness 0.20 in.
8* 118	Kim, D. H.	1972	DSC	319-390	Specimen No. 10	Composite laminate consisted of Dupont P. I. (polyimide) and E-glass fibers; resin content 22.7 weight % after cure; density 1.764 g cm ⁻³ .
9* 132	Ogawa, K. and Noguchi, Y.	1968		300-422	LE-61N	Epoxy resin reinforced by nonalkaline glass cloth; 95 x 65 x 1.08 mm; density 1.76 g cm ⁻³ ; infrared radiation method.
10 121	Campbell, M. D., Haakins, J. F., O'Bar, G. L., and Hertz, J.	1966		47-297	Specimen D	Glass fiber reinforced epoxy; unidirectional, parallel fiber, flat molding; 20 weight percent Dow DER-332 epoxy resin cured with an acid anhydride and 80% Owens-Corning high modulus YM-31-A glass fiber roving containing an HTS finish; 0.0441 thickness.
11* 121	Campbell, M. D., et al.	1966		47-297	Specimen V	Glass micro-balloon filled epoxy; 5-25 weight percent Epon 828 epoxy resin and the remainder glass micro-balloons (filled with N ₂).
12* 121	Campbell, M. D., et al.	1966		47-297	Specimen W	Similar to the above specimen except 35 weight percent resin.
13 121	Campbell, M. D., et al.	1966		47-297	Specimen E	Simulated helical filament-wound fiber reinforced epoxy 20 weight percent Owens-Corning high modulus YM-31-A glass fiber roving with an HTS finish; alternate layers of roving cross plied at angles 57 and 303 deg from the horizontal axis.
14* 135, 136	Kirillov, V. N., Avrasin, Ya. D., Efimov, V. A., and Dobrokhotova, R. A.	1973		299-562	Stektokstolits	Glass fabric laminates RJM based on epoxy-phenolic and TS-8/3-T ₂ satin weave glass fabric, titanium composition glass using 652 size; compression molding of impregnated glass fabric; density 1.940 g cm ⁻³ .
15* 135, 136	Kirillov, V. N., et al.	1973		313-567	Stektokstolits	Similar to the above specimen except heat treated at 473 K for 24 hr; density 1.930 g cm ⁻³ .
16* 135, 136	Kirillov, V. N., et al.	1973		313-573	Stektokstolits	Similar to the above specimen except heat treated at 473 K for 100 hr.

* Not shown in figure.

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17*	135, 136	Kirillov, V. N., et al.	1973		298-564	Stektokstolits	Glass fabric laminates RJM based on epoxy-phenolic and multi-ply fabric, bulky weave, type MTTS-1,6, titanium composition glass using 652 size; impregnation under vacuum or under pressure; density 2.020 g cm ⁻³ . Similar to the above specimen except heat treated at 523 K for 24 hr; density 2.000 g cm ⁻³ . Similar to the above specimen except heat treated at 523 K for 24 hr; density 1.960 g cm ⁻³ . Glass fabric laminates RJM based on modified epoxy and TS-8/3 250 glass fabric aluminoborosilicate composition glass using paraffinic size; impregnation under vacuum or under pressure; density 1.83 g cm ⁻³ . Similar to the above specimen except heat treated at 453 K for 2 hr; density 1.815 g cm ⁻³ .
18*	135, 136	Kirillov, V. N., et al.	1973		298-568		
19*	135, 136	Kirillov, V. N., et al.	1973		298-569		
20*	135, 136	Kirillov, V. N., et al.	1973		298-564		
21*	135, 136	Kirillov, V. N., et al.	1973		298-567		
22*	137	Melonas, J. V., Covington, P. C., and Pears, C. D.	1958	A	311-589	X-131 laminates	Shell X-131 epoxy resin (41.7 weight percent); "181" glass fabric, fabricated by Brunswick-Balke-Collender Co.; curing process same as above; C _p values derived from heat content studies.
23*	137	Melonas, J. V., et al.	1958	A	311-589	X-131 Fluted core sandwich	Shell X-131 epoxy resin (43.4 weight percent); "181" glass fabric; fluted core thickness 0.025 in., flute size 0.30 in. wide, 0.350 in. thick; wall thickness 0.0075 in.; fabricated by Brunswick-Balke-Collender Co.; curing process same as above; C _p values derived from heat content studies.
24	133	Lagedroest, J. F., Fabish, T. J., Eldridge, E. A., Deem, H. W., Krause, H. H., and Vaughan, D. A.	1968	I	273-623		Composite consisted of anhydride cured (nadic methyl anhydride 38.7 weight percent) epoxy novolac (Dow Chemical Co., DEN-438, 45.6 weight percent) and chopped (0.03125 in. hammer-milled) 15 weight percent fiber glass; density 1.33 and 1.29 g cm ⁻³ respectively at 293 and 573 K; measurements in argon atmosphere.
25	133	Lagedroest, J. F., et al.	1968	I	273-573		Composite consisted of anhydride cured (nadic methyl anhydride 45.6 weight percent) epoxy novolac (Dow Chemical Co. DEN-438, 53.6 weight percent) and microballoons; density 0.61 and 0.58 g cm ⁻³ respectively at 293 and 573 K; measurements in argon atmosphere.
26	134	Campbell, M. D., Hertz, J., O'Barr, G. L., and Haskins, J. F.	1965		43-296	Specimen D	Unidirectional, parallel fiber, flat molding composed of 20 weight percent Dow Chemical DER-332 epoxy resin cured with an acid anhydride and 80 weight percent Owens-Corning high modulus YM-31-A glass fiber roving containing HTS finish; cooling curve method used.
27*	134	Campbell, M. D., et al.	1965		55-295	Specimen E	Similar to the above specimen except cross-piled, unidirectional glass roving, flat molding simulating a helical wound composite; alternate layers of roving cross-piled at angles of 57 and 303 deg from the horizontal axis.
28*	138	Campbell, M. D., O'Barr, G. L., Haskins, J. F., and Hertz, J.	1965		39-297	Specimen U	Composite from CTL, division of Stuebaker; glass microballoons (Eccospheres), and Epon 828 epoxy resin (53-55 weight percent) from Shell Chemical Co.; random molding heated to 276 K and held for 1 hr; average of two runs on similar specimens.
29*	138	Campbell, M. D., et al.	1965		25-298	Specimen V	Similar to the above specimen except resin content 25 weight percent.
30*	138	Campbell, M. D., et al.	1965		30-298	Specimen W	Similar to the above specimen except resin content 35 weight percent.

* Not shown in figure.

TABLE 6-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
31*	Campbell, M.D., O'Barr, G.L., Haskins, J.F., and Hertz, J.	1965		27-299	Specimen X	Composite from above source; 5-994 glass roving; epoxy resin (30 weight percent) from U.S. Polymeric; unidirectional molding of HTS finish; glass roving and resin pressed; heated to 366 K and held for 0.5 hr; raised temperature to 427 K and held for 1.5 hr; average of runs on two similar specimens.
32	Pears, C.D., Engelke, W.T., and Thornburgh, J.D.	1964		233-655	Specimen C-1	Composite (density 1.91 g cm ⁻³ , void content 5-10 volume percent) from Raytheon Corp. containing 46 weight percent (36-59 weight percent after cure) Dow Chemical DER-332 epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin, and DMP 30, 2 parts per 100 gr. of resin; Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish; unidirectional parallel to surface layup; cured at 200 psi; heated at 366 K for 2 hr and 394 K for 2 hr.
33	Pears, C.D., et al.	1964		233-661	Specimen C-2	Composite (density 1.85 g cm ⁻³ , void content 5 volume percent) from Raytheon Corp. containing 30 weight percent (28.23 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol A; cured with nadic anhydride 80 parts in 100 gr. resin and DMP-30, 30 parts per 100 gr. of resin; Owens-Corning "E" glass fiber roving with HTS finish; 40 layers parallel to surface layup; cured at 200 psi; 2 hr at 366 K, 2 hr at 394 K.
34	Pears, C.D., et al.	1964		238-655	Specimen C-3	Composite (density 1.94 g cm ⁻³ , void content 5-10 volume percent) from Raytheon Corp. containing 40 weight percent (32.15 weight percent after cure) Dow Chemical DER-332 epoxy bisphenol cured with methyl nadic anhydride, 80 parts per 100 gr. of resin and DMP 30, 2 parts per 100 gr. of resin; Owens-Corning high modulus YM-31-A glass fiber with HTS finish; 40 layers cross-piled parallel and 66 deg from the horizontal axis; cured at 200 psi; 2 hr at 366 K and 2 hr at 394 K.
35	Pears, C.D., et al.	1964		241-661	Specimen C-4	Composite (density 2.10 g cm ⁻³ , void content 5 volume percent) from Raytheon Corp. containing 20 weight percent (17.7 weight percent after cure) Dow Chemical DER-332 (bisphenol) epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin and DMP-30, 2 parts per 100 gr. resin; Owens-Corning "E" glass fiber roving with HTS finish; layups parallel to surface, 40 layers cross-piled; cured at 200 psi; 2 hr each at 366 and 394 K.
36	Pears, C.D., et al.	1964		233-655	Specimen C-5	Composite (density 2.06 g cm ⁻³ , void content 5 volume percent) from Raytheon Corp. containing Dow Chemical 20 percent DEN-438 epoxy cured as above; Owens-Corning "E" glass fiber roving 20 end with HTS finish; unidirectional 40 layers parallel to surface; cured as above.
37	Pears, C.D., et al.	1964		211-568	Specimen d-1	Composite (density 1.97 g cm ⁻³) from Narmco containing 30 weight percent (27.7 weight percent after cure) Narmco NRC 1174/3 epoxy resin (molded from epoxy powder); Owens-Corning "E" glass flakes, 2 μ thick and 200-2000 μ diameter; layups, plies and reinforcement random; cured at 800 psi; 450 K for 2 hr.
38	Pears, C.D., et al.	1964		225-611	Specimen d-2	Similar to the above specimen except resin content 23 weight percent (26.5 weight percent after "cure"); cured at 1500 psi; 450 K for 2 hr.

* Not shown in figure.

TABLE 6-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p, cal g⁻¹ K⁻¹]

T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p	T	C _p
---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------	---	----------------

* Not shown in figure.

[illegible]

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of glass fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific resin, curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost and specific properties desired. The softening point of cured epoxy resin is near 450 K. No experimental data for the heat of fusion/softening of such cured epoxy resin were located in the literature.

d. Thermal Linear Expansion

There are 73 sets of experimental data available for the thermal linear expansion of glass fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 6-8. The experimental data are tabulated in Table 6-9 and partially shown in Figures 6-3A through 6-3F. These data sets cover the following types of composites:

E-Glass/Epon 828 epoxy (curves 6-17),
 YM-31-A glass/DER 332 epoxy (curves 19-21, 24-29, 36-41, and 52-54),
 E-Glass/DER 332 epoxy (curves 30-35 and 42-45),
 E-Glass/DEN 438 epoxy (curves 18 and 46-51),
 S-Glass/DER 332 epoxy (curves 62-65), and
 S-Glass/Epon 828 epoxy (curves 66-69).

It is worth noting that, although there are several data sets available for each of composites, the forms of glass used in the same type of composite are different. The various forms commonly used are fibers, rovings, and filaments. Similarly, the curing agents and curing processes used are also different. Most of the composites do not show reasonably stable behaviour after first heating and cooling cycle, resulting in scattered thermal linear expansion data. Secondly, most of these data sets are not corroborated. These make the data analysis very difficult. It is practically impossible from the available information to separate out the effects of individual factors affecting the thermal expansion of composites, i.e., fiber type and content, epoxy type and content, curing agent, curing process, and heating/cooling cycles. It may be safe to assume that the effect due to curing agent is smaller as compared with that due to curing process.

Since the transverse thermal linear expansion (measured across the thickness) is several times higher than the longitudinal thermal linear expansion (measured along fiber plane), these two are discussed separately in the following sections. The provisional values generated are based mainly on the data for stable thermal cycle.

Expansion Along Fiber Direction (Longitudinal)

(1) YM-31-A Glass Fiber/DER-332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3A are derived primarily from the measurements of Campbell et al. [121] (curve 19), Pears et al. [126] (curves 24 and 25), and Haskins et al. [120] (curve 54). These values are for cured composite with epoxy content of 20-40 weight percent and with parallel glass fiber

reinforcement. This type of composite begins to degrade near 550 K. The uncertainty of the values is about $\pm 10\%$. It is worth noting that the thermal linear expansion for this composite is similar to YM-31-A glass fiber/Epon 828 composite (curve 6). Similar composite with cross-plyed fibers has slightly higher expansion and shows considerable scatter in the thermal linear expansion data (curves 36 and 37).

(2) E-Glass Fiber/DER-332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3B are derived primarily from the measurements of Pears et al. [126] (curves 30 and 31). These values are for cured composite with epoxy content of about 30 weight percent and with parallel glass fiber reinforcement. This type of composite begins to decompose near 550 K. The uncertainty of the provisional values is about $\pm 10\%$. This composite has a lower longitudinal thermal linear expansion than YM-31-A glass fiber/DER 332 epoxy composite and E-glass fiber/Epon 828 epoxy composite. The composite with cross-plyed fibers shows considerable scatter in the thermal linear expansion data and the expansion data during heating and cooling cycles are not reproducible.

(3) E-Glass Fiber/DEN 438 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3C are derived primarily from the measurements of Pears et al. [126] (curves 46 and 47). These values are for cured composite with epoxy content of 20 weight percent and with parallel glass fiber reinforcement. The uncertainty of the provisional values is $\pm 10\%$. This composite begins to degrade near 600 K and has an intermediate thermal linear expansion between YM-31-A glass fiber/DER 332 epoxy composite and E-glass fiber/DER 332 epoxy composite.

Expansion Along Fiber Thickness (Transverse)

The thermal linear expansion in the fiber thickness direction is generally about 2 to 5 times higher than that in the direction along fiber plane (reinforcement direction). Unlike the expansion in the reinforcement direction, the thermal linear expansion along the fiber thickness is greatly affected by warpage and delamination, especially at temperatures near 475 K. Therefore, the available data in the fiber thickness direction show considerable scatter making the data less useful for the purpose of analysis.

(1) YM-31-A Glass Fiber/DER 332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3D are derived primarily from the measurements of Pears et al. [126] (curves 25 and 26) and of

Haskins et al. [120] (curves 52 and 53). These values are for cured composite with epoxy content of 20-30 weight percent and with parallel glass fiber reinforcement. The uncertainty of these values is about $\pm 15\%$. The composite with cross-ply fibers has considerably higher and more irregular expansion (curves 38 and 39).

(2) E-Glass Fiber/DER 332 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3E are derived primarily from the measurements of Pears et al. [126] (curves 32 and 33). These values are for cured composite with about 20 weight percent epoxy resin and with parallel glass fiber reinforcement. The uncertainty of these values is $\pm 15\%$. The composite with cross-ply fiber shows abnormally high thermal linear expansion above 475 K, possibly due to delamination of the composite.

(3) E-Glass Fiber/DEN 438 Epoxy Composite

The provisional values tabulated in Table 6-7 and shown in Figure 6-3F are derived primarily from the measurements of Pears et al. [126] (curves 48 and 49). These values are for cured composite with epoxy content of 20 weight percent and with parallel glass fiber reinforcement. The uncertainty of these values is $\pm 15\%$. This composite has higher expansion than similar YM-31-A glass fiber/DER 332 composite and E-glass fiber/DER 332 composite.

The values of the instantaneous coefficient of thermal linear expansion, α , for the above composites are obtained by differentiation of empirical equations which are used to fit the provisional thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about $\pm 20\%$.

TABLE 6-7 PROVISIONAL THERMAL LINEAR EXPANSION
OF GLASS FIBER EPOXY COMPOSITES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

a. Expansion Along Fiber Direction

T	YM-31-A/DER-332		E/DER-332		E/DEN-438	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α	$\Delta L/L_0$	α
25	-0.133	3.9				
30	-0.131	4.0				
40	-0.127	4.1				
50	-0.123	4.2				
60	-0.119	4.3				
70	-0.115	4.4				
80	-0.110	4.5				
90	-0.106	4.5				
100	-0.101	4.6				
150	-0.077	5.0				
200	-0.051	5.3				
250	-0.024	5.5				
273.15	-0.011	5.6				
293	0.000	5.7	0.000	4.4	0.000	5.1
300	0.004	5.7	0.003	4.4	0.004	5.1
350	0.033	5.8	0.025	4.5	0.029	5.2
400	0.062	5.8	0.048	4.6	0.056	5.3
450	0.091	5.8	0.071	4.6	0.082	5.4
500	0.120	5.8	0.094	4.7	0.109	5.4
550	0.148	5.8	0.118	4.8	0.137	5.5

b. Expansion Along Fiber Thickness

T	YM-31-A/DER-332		E/DER-332		E/DEN-438	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α	$\Delta L/L_0$	α
25	-0.643	22.1				
30	-0.632	22.1				
40	-0.610	22.1				
50	-0.588	22.2				
60	-0.566	22.2				
70	-0.544	22.3				
80	-0.521	22.4				
90	-0.499	22.5				
100	-0.476	22.6				
150	-0.361	23.4				
200	-0.242	24.5				
250	-0.115	26.1				
273.15	-0.054	26.9				
293	0.000	27.7	0.000	12.7	0.000	27.8
300	0.019	28.0	0.009	13.5	0.020	29.1
350	0.164	30.2	0.089	18.7	0.188	38.3
400	0.322	32.8	0.196	23.9	0.403	47.5
450	0.494	35.8	0.328	29.0	0.663	56.7
500	0.682	39.2	0.486	34.2	0.970	66.0
550	0.886	42.9	0.670	39.3	1.324	75.4

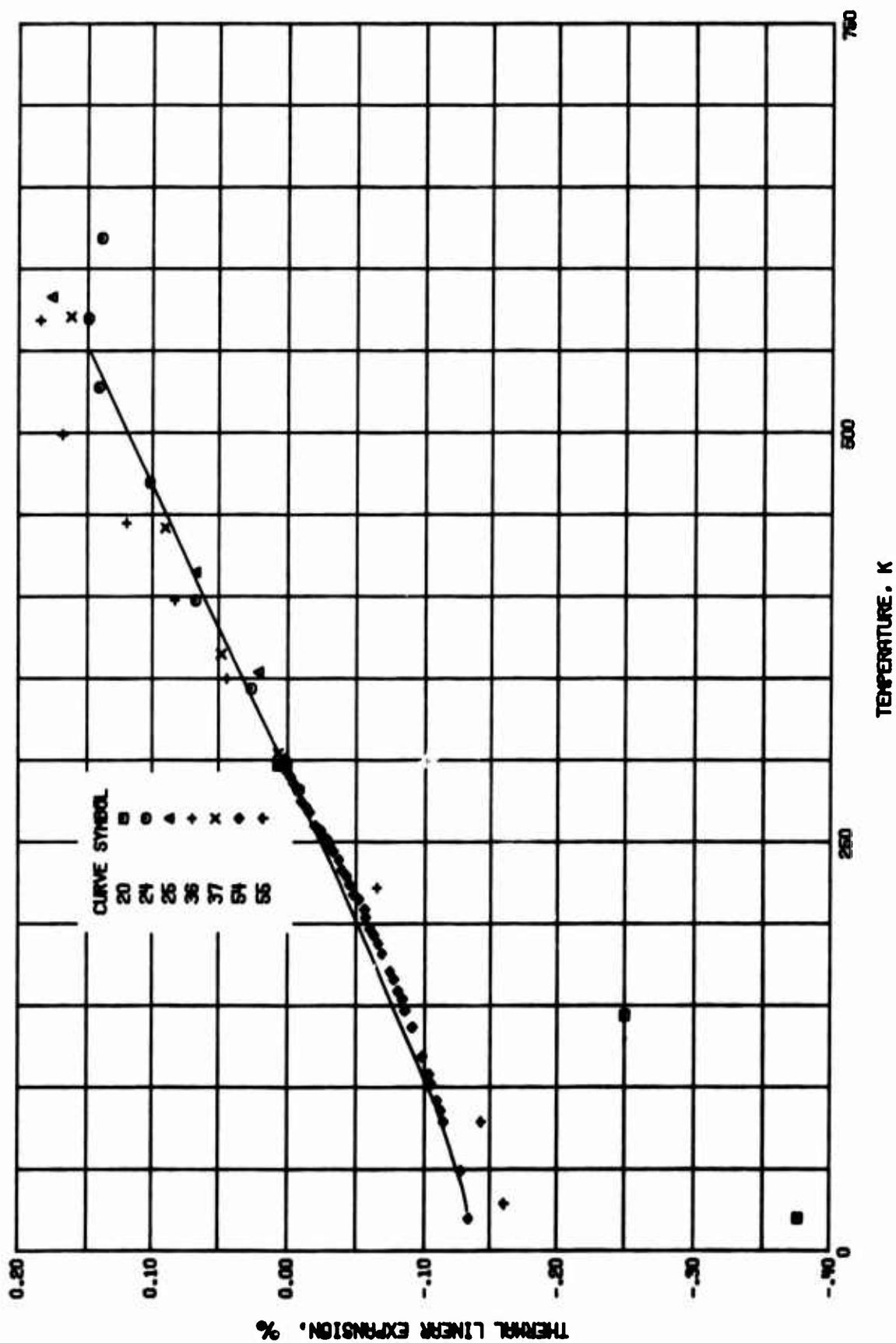


FIGURE 6-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF YN-31-A GLASS FIBER DER 332 EPOXY COMPOSITES .

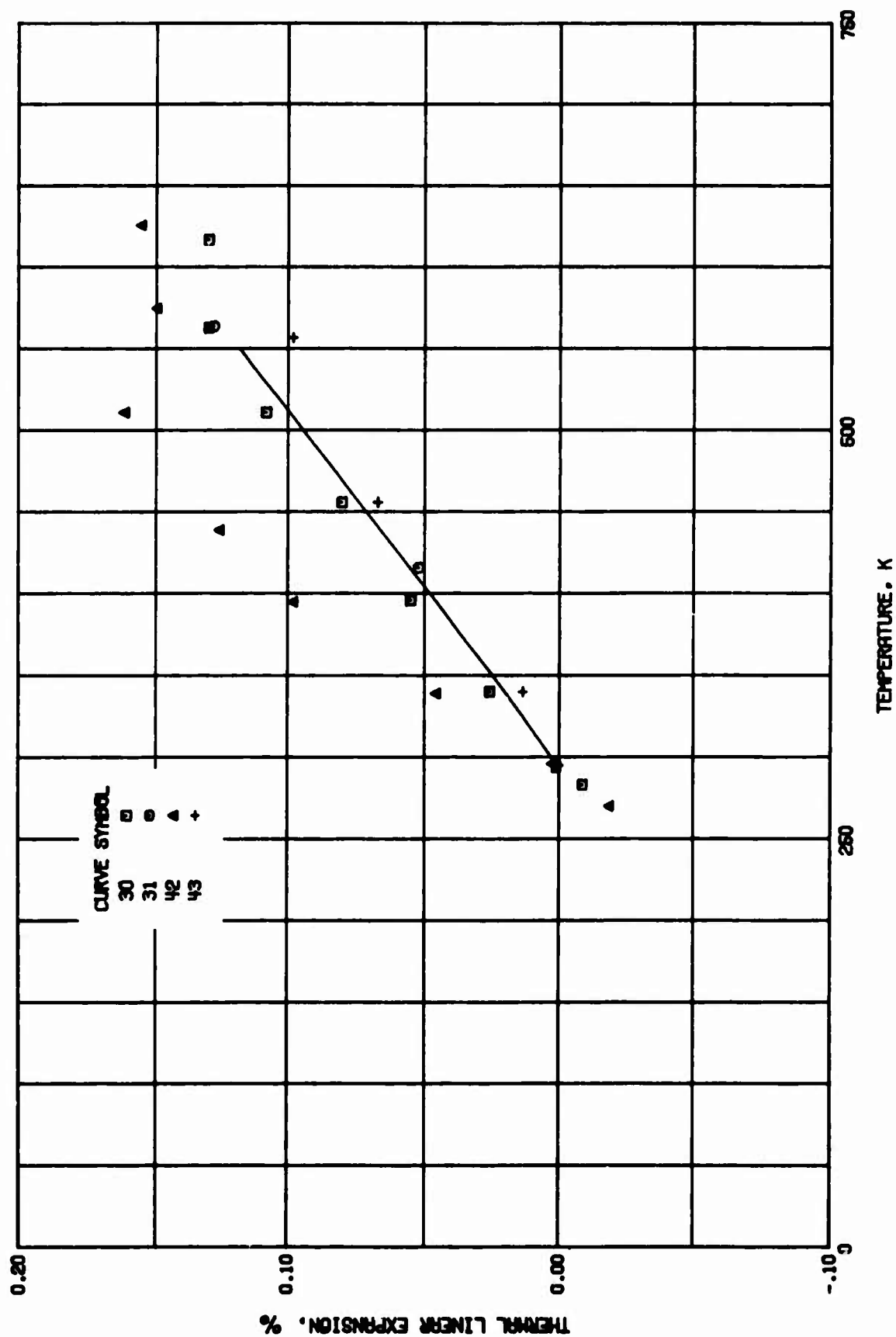


FIGURE 6-38. LONGITUDINAL THERMAL LINEAR EXPANSION OF E-GLASS FIBER DER 332 EPOXY COMPOSITES .

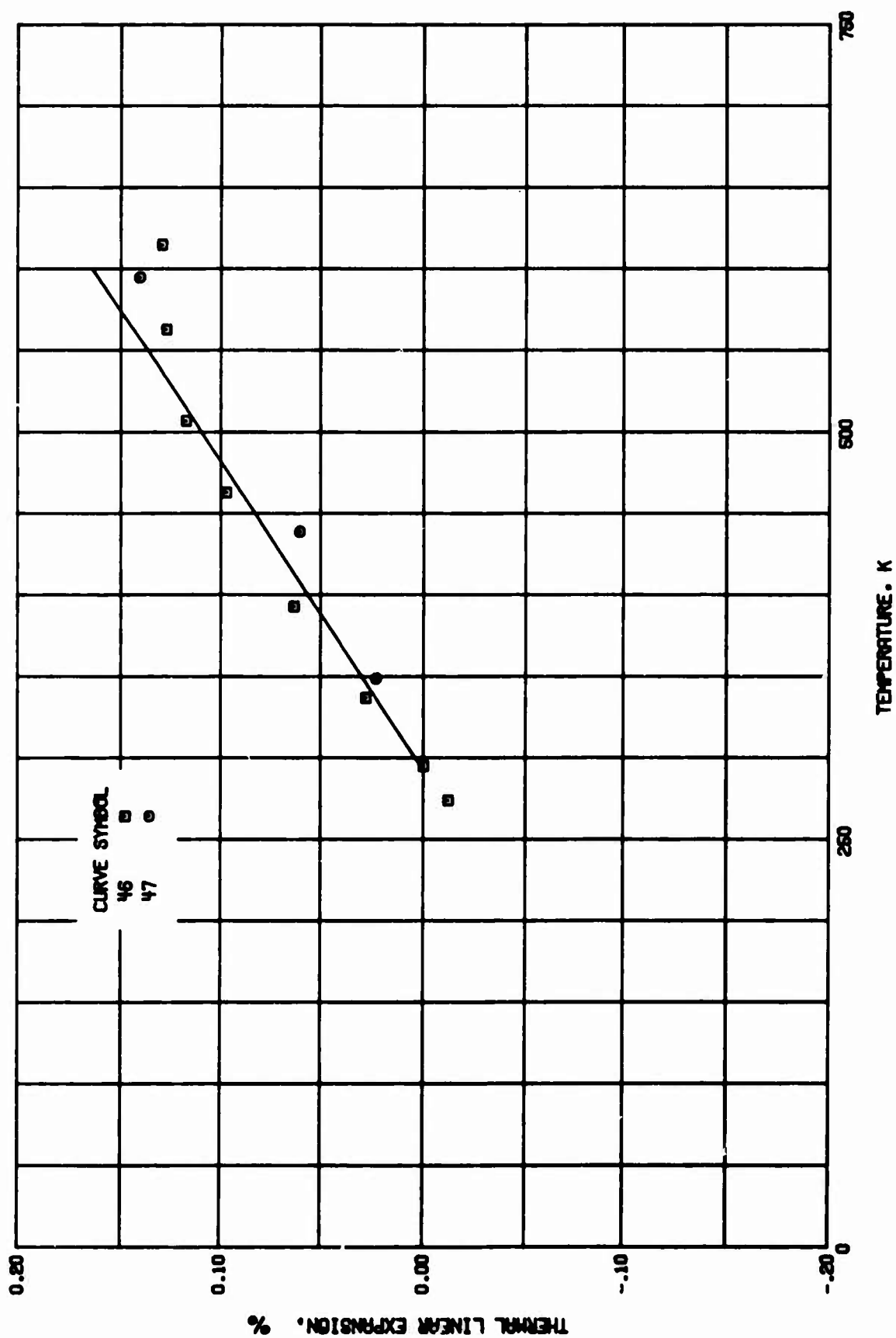


FIGURE 6-3C. LONGITUDINAL THERMAL LINEAR EXPANSION OF E-GLASS FIBER DEN 438 EPOXY COMPOSITES .

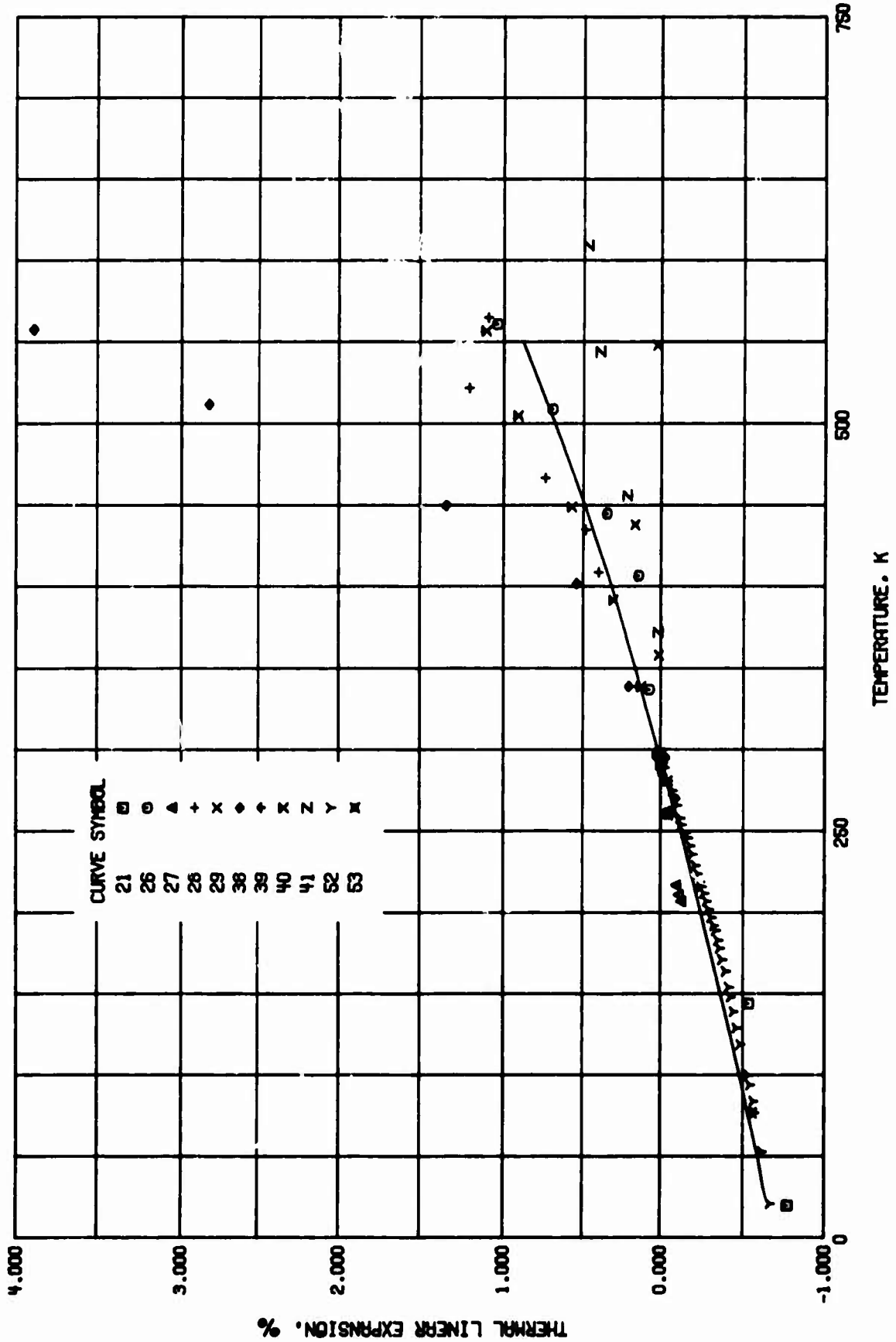


FIGURE 6-30. TRANSVERSE THERMAL LINEAR EXPANSION OF YH-31-A GLASS FIBER DER 332 EPOXY COMPOSITES .

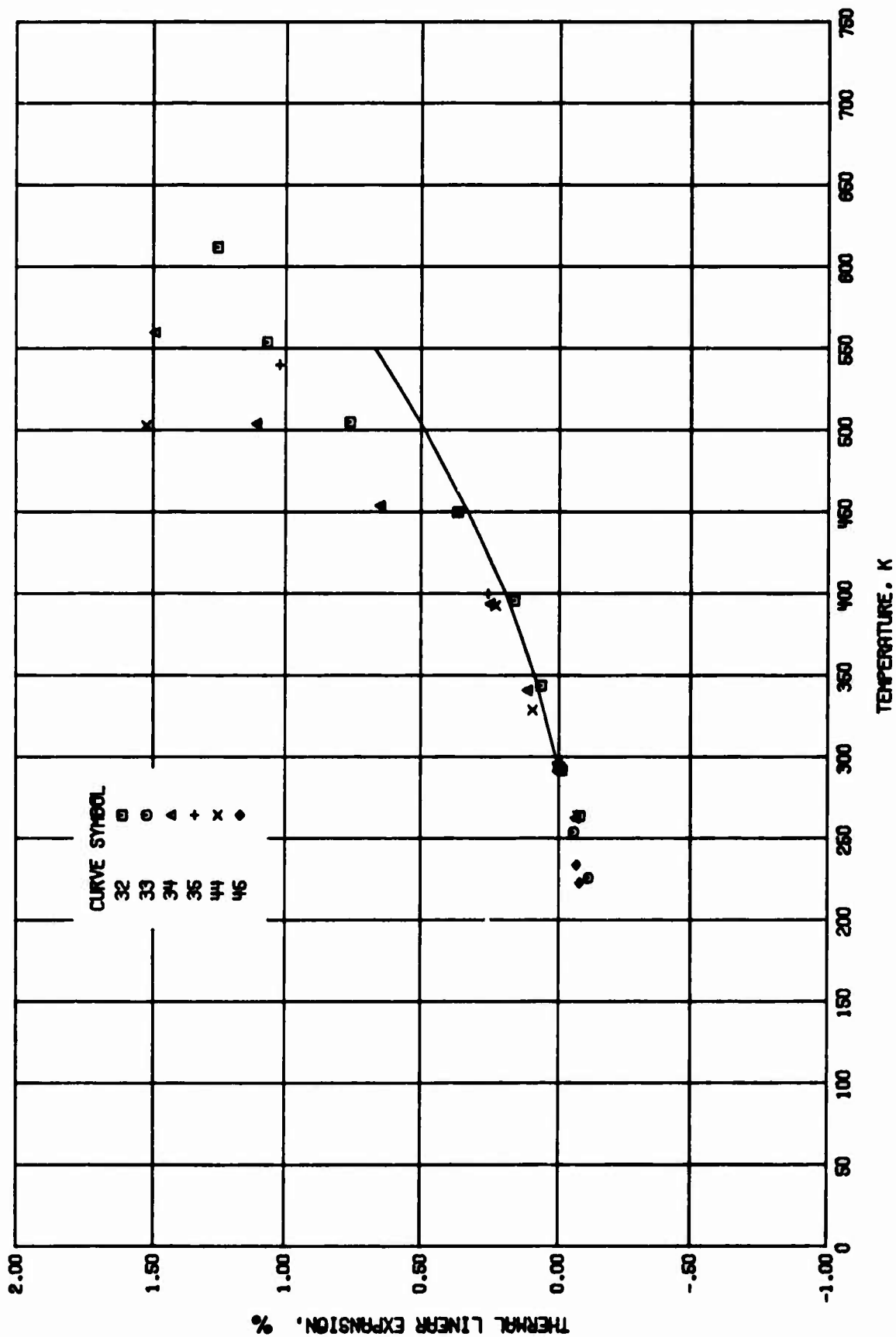


FIGURE 6-3E. TRANSVERSE THERMAL LINEAR EXPANSION OF E-GLASS FIBER DER 332 EPOXY COMPOSITES .

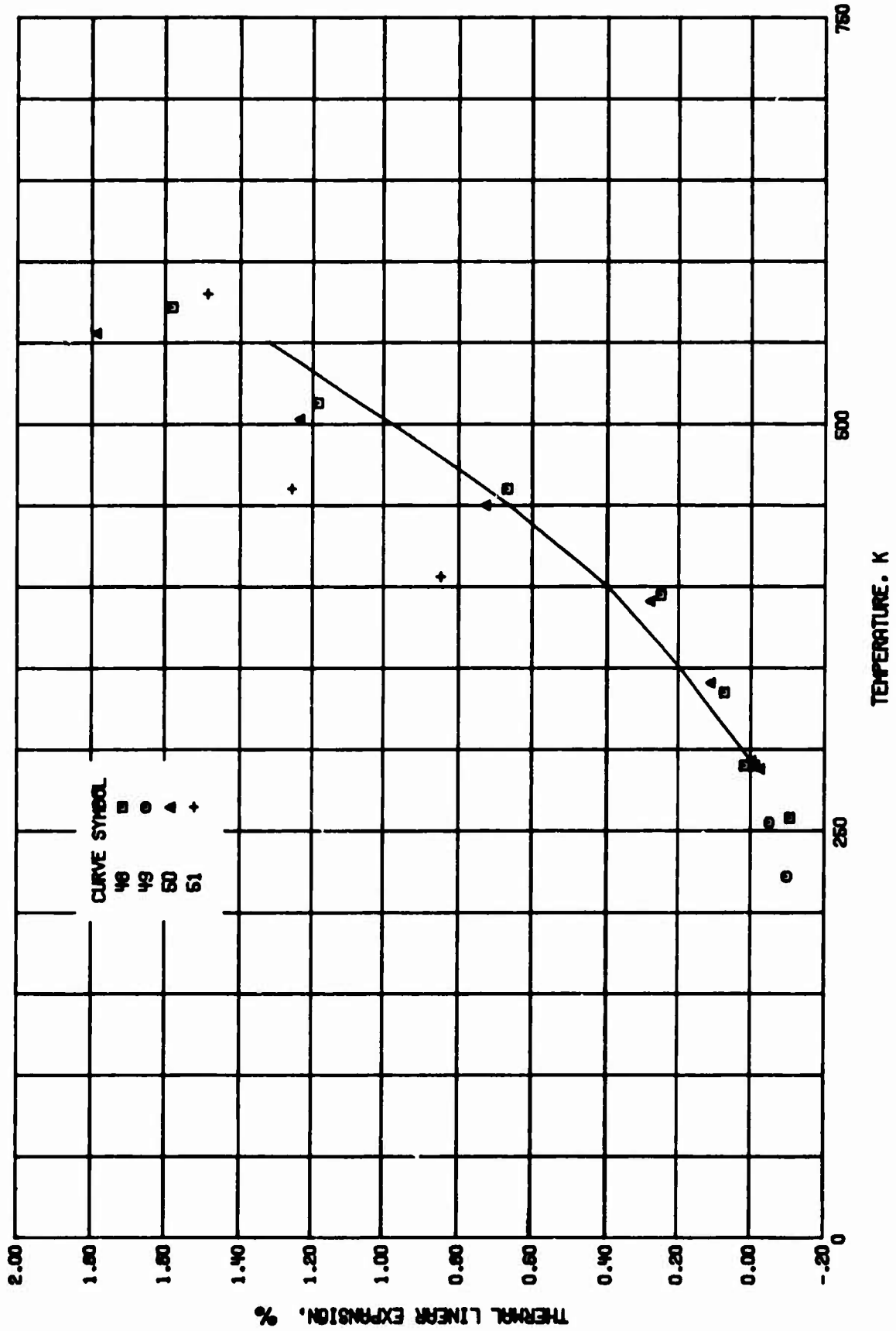


FIGURE 6-3F. TRANSVERSE THERMAL LINEAR EXPANSION OF E-GLASS FIBER DEN 438 EPOXY COMPOSITES .

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1* 139	Gulati, S. T. and Plummer, W. A.	1972	L	153-327	LRG-18R	Longitudinal bar of quasi-isotropic composite fabricated using scotchply (3 M Co.) reinforced plastic type 1002 containing 44 volume percent of E-glass fiber in epoxy resin.
2* 139	Gulati, S. T. and Plummer, W. A.	1972	L	153-308	LRG-41	Similar to the above specimen except transverse bar; zero-point correction is 0.009%.
3* 140, 141	Kritsuk, A. A.	1972	L	78-476	GRP	Glass reinforced plastic cut with diamond disc from sheets prepared by "wet" winding on a metal mandrel and cured under ~10 kg/cm ² pressure; epoxy-amine formulation (ED-6 epoxy resin hardened with triethanolamine titanate) used as binder and nonalkaline NS/6 glass fiber used as filler; epoxy content 19.5 weight percent; measurements along the reinforcement; zero-point correction -0.005%.
4* 140, 141	Kritsuk, A. A.	1972	L	78-370		Similar to the above specimen except measurements along transverse direction; zero-point correction is -0.018%.
5* 140, 141	Kritsuk, A. A.	1972	L	78-420		Similar to the above specimen except measurements for glass reinforced plastic with 1:1 structure; zero-point correction is -0.003%.
6* 142	General Electric Co.	1964	V	122-478		Glass fibers ("E" glass) from Pittsburgh Glass Co. placed in shell Epon 828 solid fibers placed longitudinally; specimen cured 2 hr at 366 K, 4 hr at 394 K, and 6 hr at 422 K; soaked 30 min at 116 K and tested with heating at 0.6 deg/min; expansion measured parallel to fibers; zero-point correction is -0.097%.
7* 142	General Electric Co.	1964	V	133-477		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.197%.
8* 142	General Electric Co.	1964	V	118-478		Similar to the above specimen except expansion measured transverse to solid fibers; zero-point correction is -0.220%.
9* 142	General Electric Co.	1964	V	118-478		The above specimen; second run; zero-point correction is -0.295%.
10* 142	General Electric Co.	1964	V	117-478		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.428%.
11* 142	General Electric Co.	1964	V	117-478		Similar to the above specimen; second cycle; zero-point correction is -0.394%.
12* 142	General Electric Co.	1964	V	118-477		Similar to the above specimen except solid fibers placed in 90 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.175%.
13* 142	General Electric Co.	1964	V	118-453		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.217%.
14* 142	General Electric Co.	1964	V	114-478		Similar to the above specimen except solid fibers placed in 90 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.175%.
15* 142	General Electric Co.	1964	V	114-454		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.245%.
16* 142	General Electric Co.	1964	V	117-478		Similar to the above specimen except solid fibers placed in 60 deg mesh oriented diagonally with respect to the expansion direction; zero-point correction is -0.261%.
17* 142	General Electric Co.	1964	V	117-478		Similar to the above specimen except hollow glass fibers; zero-point correction is -0.337%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18*	Lagedrost, J. F., Fabish, T. J., Eldridge, E. A., Deem, H. W., Krause, H. H., and Vaughan, D. A.	1968	L	293-593		Composite consisted of anhydride cured (nadic methyl anhydride 38.7 weight percent) epoxy novolac (Dow Chemical Co. DEN-438, 45.6 weight percent) and chopped (1/32 in. hammer-milled) 15 weight percent fiber glass; density 1.33 g cm ⁻³ at 293 K and 1.20 g cm ⁻³ at 573 K; measurements in argon atmosphere; zero-point correction is 0.02%.
19*	Campbell, M. D., Has'ina, J. F., O'Barr, G. L., and Hertz, J.	1966	L	20-297	Specimen D	Owens-Corning high modulus YM-31-A glass fiber roving with HTS finish, and 20 weight percent Dow Chemical DER-332 epoxy resin cured with acid anhydride, unidirectional, parallel fibers; flat molding; average density 2.01 g cm ⁻³ ; zero-point correction is 0.002%.
20	Campbell, M. D., et al.	1966	L	20-297	Specimen E	Simulated helical filament wound fiber-reinforced epoxy; 20 weight percent (36.2 weight percent average of two panels) Dow Chemical DER-332 epoxy resin cured with acid anhydride; Owens-Corning YM-31-A glass fiber roving with HTS finish; alternat layers of roving cross piled at angles of 57 and 303 deg from horizontal axis; density 1.94 g cm ⁻³ ; expansion measured normal to the thickness direction; normal to 57 deg ply; zero-point correction is -0.007%.
21	Campbell, M. D., et al.	1966	L	20-297	Specimen E	Similar to the above specimen; expansion measured along the thickness direction; parallel to 57 deg ply; zero-point correction is -0.003%.
22*	Campbell, M. D., O'Barr, G. L., Haskins, J. F., and Hertz, J.	1965	L	20-296		Composite system from CTL, division of Studbaker; S-994 glass roving; E-787 epoxy resin (30 weight percent) from U. S. Polymeric; specimen unidirectional molding of HTS finish; glass roving and resin pressed; heated to 366 K and held for 1 1/2 hr; raised temperature to 427 K and held for 1.5 hr; average of runs on two similar specimens; measurements along thickness direction; zero-point correction is 0.005%.
23*	Campbell, M. D., et al.	1965	L	20-296		The above specimen; measurements parallel to fibers; zero-point correction is 0.001%.
24	Pears, C. D., Engelke, W. T., and Thornburgh, J. D.	1964	L	282-619	Material C1	Composite (density 1.91 g cm ⁻³ , void content 5-10 volume percent) from Raytheon Corp. containing 40 weight percent DER-332 epoxy cured with methyl nadic anhydride 80 parts per 100 gr. resin and DMP 30, 2 parts per 100 parts of resin; Owens-Corning high modulus YM31-A glass fiber roving; HTS finish; unidirectional parallel to surface lay up; cured at 200 psi; heated at 366 K for 2 hr and 394 K for 2 hr; heating cycle; measurements parallel to the fiber direction; zero-point correction is 0.003%.
25	Pears, C. D., et al.	1964	L	583-296	Material C1	The above specimen; cooling cycle; zero-point correction is 0.224%.
26	Pears, C. D., et al.	1964	L	261-561	Material C1	The above specimen; expansion measured in the thickness direction; heating cycle; specimen continued to expand on cooling; zero-point correction is 0.05%.
27	Pears, C. D., et al.	1964	L	262-207	Material C1	The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is -0.01%.
28	Pears, C. D., et al.	1964	L	260-565	Material C1	The above specimen; expansion measured in the perpendicular to the reinforcement direction; heating cycle; zero-point correction is -0.006%.
29	Pears, C. D., et al.	1964	L	548-293	Material C1	The above specimen; expansion measured in the perpendicular to the reinforcement direction; cooling cycle; zero-point correction is 1.748%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
30 126	Pears, C.D., Engelle, W.T., and Thornburgh, J.D.	1964	L	283-617	Material C2	Composite (density 1.85 g cm^{-3} , void content 5 volume percent) from Raytheon Corp. containing 30 weight percent (28.23 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol A cured with nadic anhydride 80 parts per 100 gr. resin and DMP-30, 30 parts per 100 parts of resin; Owens-Corning "E" glass fiber roving; HTS finish; 40 layers parallel to surface lay up; cured at 200 psi, 2 hr at 366 K, 2 hr at 394 K; heating cycle; expansion measured in the direction parallel to reinforcement.
31 126	Pears, C.D., et al.	1964	L	564-296	Material C2	The above specimen; measurements in the direction parallel to reinforcement; cooling cycle; zero-point correction is 0.119%.
32 126	Pears, C.D., et al.	1964	L	264-612	Material C2	The above specimen; expansion measured in the thickness direction; heating cycle; zero-point correction is -0.004%.
33 126	Pears, C.D., et al.	1964	L	254-226	Material C2	The above specimen; expansion measured in the thickness direction; cooling cycle.
34 126	Pears, C.D., et al.	1964	L	263-560	Material C2	The above specimen; expansion measured in the direction perpendicular to the reinforcement; heating cycle; zero-point correction is 0.006%.
35 126	Pears, C.D., et al.	1964	L	540-294	Material C2	The above specimen; expansion measured in the direction perpendicular to the reinforcement; cooling cycle; zero-point correction is 1.423%.
36 126	Pears, C.D., et al.	1964	L	222-569	Specimen C-3	Composite (density 1.94 g cm^{-3} , void content 5-10 volume percent) from Raytheon Corp., containing 40 weight percent (32.15 weight percent after cure) Dow Chemical DER 332 epoxy bisphenol cured with methyl nadic anhydride, 80 parts per 100 grs of resin, and DMP 30, 2 parts per 100 grs of resin; Owens-Corning high modulus YM-31-A glass fiber roving; HTS finish; 40 layers cross plied parallel and 66 deg from the horizontal axis; cured at 200 psi; 2 hr at 366 K, and 2 hr at 394 K; heating cycle; expansion measured in the direction of material.
37 126	Pears, C.D., et al.	1964	L	571-304	Specimen C-3	The above specimen; expansion measured in the direction of material; cooling cycle; zero-point correction is 0.312%.
38 126	Pears, C.D., et al.	1964	L	270-558	Specimen C-3	The above specimen; expansion measured in the thickness direction; heating cycle; zero-point correction is 0.026%.
39 126	Pears, C.D., et al.	1964	L	435-294	Material C-3	The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is -0.321%.
40 126	Pears, C.D., et al.	1964	L	281-557	Material C-3	The above specimen; expansion measured in the direction perpendicular to fiber orientation; heating cycle; zero-point correction is -0.014%.
41 126	Pears, C.D., et al.	1964	L	609-291	Material C-3	The above specimen; expansion measured in the direction perpendicular to fiber orientation; cooling cycle; zero-point correction is 1.557%.
42 126	Pears, C.D., et al.	1964	L	270-626	Material C-4	Composite (density 2.10 g cm^{-3} , void content 5 volume percent) from Raytheon Corp., containing 20 weight percent (17.7 weight percent after cure) Dow Chemical DER-332 (bisphenol) epoxy cured with methyl nadic anhydride 80 parts per 100 grs resin and DMP-30, 2 parts per 100 grs resin; Owens-Corning "E" glass fiber roving, HTS finish; lay ups parallel to surface, 40 layers cross plied; cured at 200 psi; 2 hr at 366 K, 2 hr at 394 K; expansion measured in the direction of fiber; heating cycle; zero-point correction is 0.003%.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition	Notes, Specifications, and Remarks
43 126	Pears, C.D., Egglese, W.T., and Thornburgh, J.D.	1964	L	537-295	Material C-4		The above specimen; expansion measured in the direction of fiber; cooling cycle; zero-point correction is 0.064%.
44 126	Pears, C.D., et al.	1964	L	264-503	Material C-4		The above specimen; expansion measured in the thickness direction; heating cycle.
45 126	Pears, C.D., et al.	1964	L	234-223	Material C-4		The above specimen; expansion measured in the thickness direction; cooling cycle; zero-point correction is 0.036%.
46 126	Pears, C.D., et al.	1964	L	274-615	Material C-5		Composite (density 2.06 g cm ⁻³ , void content 5 volume percent) from Raytheon Corp., containing 20 weight percent (21.06 weight percent after cure) Dow Chemical DEN-438 epoxy cured as above; Owens-Corning "E" glass fiber roving 20 end, HTS finish, unidirectional 40 layers parallel to surface; cured at 200 psi; 2 hr at 366 K, 2 hr at 394 K; expansion measured parallel to the reinforcement direction; heating cycle.
47 126	Pears, C.D., et al.	1964	L	595-349	Material C-5		The above specimen; expansion measured parallel to the reinforcement direction; cooling cycle; zero-point correction is 0.096%.
48 126	Pears, C.D., et al.	1964	L	258-572	Material C-5		The above specimen; measurement in the thickness direction; heating cycle; zero-point correction is 0.010%.
49 126	Pears, C.D., et al.	1964	L	255-222	Material C-5		The above specimen; measurement in the thickness direction; cooling cycle.
50 126	Pears, C.D., et al.	1964	L	288-615	Material C-5		The above specimen; measurement in the perpendicular to reinforcement; heating cycle.
51 126	Pears, C.D., et al.	1964	L	648-406	Material C-5		The above specimen; measurement in the perpendicular to reinforcement; cooling cycle; zero-point correction is 3.028%.
52 120	Haskins, J.F., Campbell, M.D., Hertz, J., and Percy, J.L.	1964	L	21-298			Owens-Corning high modulus YM-31-A glass fiber roving (90 weight percent) with HTS finish; Dow Chemical DER-332 epoxy resin cured with acid anhydride; unidirectional, parallel fibers, flat molding; specimen 0.117 x 0.117 x 20 in. stacked and loaded by series of 0.5 in. wide pieces in the thickness direction from the panel; zero-point correction is 0.003%.
53 120	Haskins, J.F., et al.	1964	L	77-298			The above specimen; immediately cycled while still in the dilatometer; third cycle; expansion measured in the thickness direction; zero-point correction is 0.005%.
54 120	Haskins, J.F., et al.	1964	L	20-298			The above specimen; expansion measured parallel to reinforcement; first run; using vertical dilatometer in subliquid hydrogen temperature and data corrected; zero-point correction is 0.003%.
55 143	Brecha, H. and Haldemann, W.	1965	L	5-301	S994/HTS		S994/HTS glass roving with 19 weight percent Union Carbide ERL 2256/MPDA epoxy resin; average density 2.1 g cm ⁻³ .
56* 129, 130	Toth, L.W., Boller, T.J., Fischer, L.R., Kariotis, A.H., and Yoder, F.D.	1965	L	20-297	BFW		Reinforced plastic using S/HTS glass from U.S. Polymeric Chem. Inc.; 20-end roving filament wound in bidirectional (0-90 deg., 1/1 dispersion) orientation; preimpregnated with 19.10% E-787 epoxy system; expansion measured normal to reinforcement.
57* 129, 130	Toth, L.W., et al.	1965	L	20-297	BFW		The above specimen; second run.
58* 129, 130	Toth, L.W., et al.	1965	L	20-297	BFW		Similar to the above specimen except expansion measured parallel to the reinforcement.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
59* 129, 130	Toth, L. W., et al.	1965	L	20-297	BFW	The above specimen; second run.
60* 129, 130	Toth, L. W., et al.	1965	L	20-297	UFW	Similar to the above specimen except filament wound in unidirectional orientation; resin content 18.03%; expansion measured normal to reinforcement.
61* 129, 130	Toth, L. W., et al.	1965	L	20-297	UFW	The above specimen except expansion measured parallel to reinforcement.
62* 130	Toth, L. W., Boller, T. J., Butcher, I. R., Karlotis, A. H., and Yoder, F. D.	1966	L	77-297	S Glass- DER 332/BF ₃	Reinforced plastic consisted of 17.4% DER-332 epoxy resin; BF ₃ curing agent and 20-end S/HTS glass roving; expansion measured parallel to reinforcement.
63* 130	Toth, L. W., et al.	1966	L	77-297	S Glass- DER 332/BF ₃	The above specimen; expansion measured normal to reinforcement.
64* 130	Toth, L. W., et al.	1966	L	77-297	S Glass- DER 332/DEH 50	Reinforced plastic, consisted of 19% DER-332 epoxy resin, DEH 50 curing agent and 20-end S/HTS glass roving; expansion measured parallel to reinforcement.
65* 130	Toth, L. W., et al.	1966	L	77-297	S Glass- DER 332/DEH 50	The above specimen; expansion measured normal to reinforcement.
66* 144	Soffer, L. M. and Molho, R.	1968	L	22-294	Resin 2 Laminate	Resin 2 laminates were prepared from Epon 828/DSA/1040/BDMA resin system by in-process winding (S-901 glass filament) on a 6 x 8 in. flat mandrel, after cure the panels were cut and sanded into rectangular beam specimen, three specimens prepared for testing in the longitudinal (parallel to the filament orientation) direction; resin content 17.1 weight percent.
67* 144	Soffer, L. M. and Molho, R.	1968	L	17-294	Resin 2 Laminate	Similar to the above specimen except three specimens were prepared for testing in the transverse (normal to the filament orientation) direction; resin content 14.4 weight percent.
68* 144	Soffer, L. M. and Molho, R.	1968	L	17-294	Resin 4A Laminate	Resin 4A laminates were prepared from Epon 828/Epon 871/L-100/MOCA resin system by applying on the mandrel alternate layers of roving (S-901 glass filament) and coating of resin applied by brush; a heat gun trained on the mandrel maintained a temperature of 338 K; after cure the panels were cut and sanded into rectangular beam specimens, three specimens prepared for testing in the longitudinal (parallel to the filament orientation) direction; resin content 37.7 weight percent.
69* 144	Soffer, L. M. and Molho, R.	1968	L	17-294	Resin 4A Laminate	Similar to the above specimen except three specimens were prepared for testing in the transverse (normal to the fiber orientation) direction; resin content 30.4 weight percent.
70* 145	Kahala, L. L.	1974	L	293-411	S-glass	UD (unidirectional) composite made from prepregged S-glass (Ferro, S-1014) yarn bundles by the "leaky" pressure molding technique; fiber content 69 volume percent; void content 2.5% ignored in the calculation; specimen length 50 mm; cycled 2-3 times from room temperature to 423 K to relieve non-equilibrium thermal stresses; measurements in transverse direction; heating cycle; zero-point correction is 0.006%.
71* 145	Kahala, L. L.	1974	L	411-293	S-glass	The above specimen; cooling cycle; zero-point correction is 0.006%.

* Not shown in figure.

TABLE 6-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
72*	145	Kahala, L. L.	1974	L	293-399	S-glass	The above specimen; measurements in the axial direction; heating cycle; zero-point correction is 0.001%.
73*	145	Kahala, L. L.	1974	L	399-293	S-glass	The above specimen; cooling cycle; zero-point correction is 0.001%.

* Not shown in figure.

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
<u>CURVE 41</u>		<u>CURVE 47</u>		<u>CURVE 52 (cont.)</u>		<u>CURVE 54 (cont.)</u>		<u>CURVE 58*</u>	
609	0.473	595	0.141	139	-0.446	159	-0.081	20	-0.153
544	0.394	439	0.060	148	-0.428	166	-0.078	77	-0.141
456	0.216	349	0.023	154	-0.415	171	-0.075	197	-0.075
372	0.018	<u>CURVE 48</u>		164	-0.396	182	-0.069	297	0.003
291	0.000	258	-0.106	171	-0.376	188	-0.066	<u>CURVE 59*</u>	
<u>CURVE 42</u>		178	-0.362	193	-0.063	197	-0.060	<u>CURVE 66*</u>	
270	-0.019	290	-0.010	183	-0.351	204	-0.057	17	-0.047
296	0.003	290	0.016	189	-0.338	204	-0.057	33	-0.048
339	0.046	335	0.071	192	-0.327	209	-0.056	61	-0.047
395	0.098	395	0.251	197	-0.311	215	-0.052	89	-0.045
439	0.126	460	0.667	202	-0.294	218	-0.048	116	-0.041
511	0.162	513	1.185	207	-0.283	224	-0.045	144	-0.036
575	0.150	572	1.582	212	-0.267	229	-0.043	172	-0.031
626	0.156	<u>CURVE 49</u>		216	-0.253	233	-0.039	200	-0.025
<u>CURVE 43</u>		255	-0.051	219	-0.244	239	-0.037	227	-0.018
557	0.098	222	-0.098	224	-0.229	244	-0.033	255	-0.010
456	0.067	<u>CURVE 50</u>		229	-0.214	248	-0.030	283	-0.004
340	0.014	288	-0.024	236	-0.196	252	-0.028	294	0.000
295	0.006	293	0.000	241	-0.183	257	-0.024	<u>CURVE 61*</u>	
<u>CURVE 44</u>		391	0.282	246	-0.167	260	-0.020	20	-0.059
264	-0.070	450	0.727	249	-0.151	268	-0.016	77	-0.054
294	-0.006	503	1.239	254	-0.132	271	-0.014	197	-0.029
329	0.098	556	1.789	258	-0.122	275	-0.010	297	0.001
393	0.231	615	1.849	266	-0.102	282	-0.007	<u>CURVE 62*</u>	
503	1.524	<u>CURVE 51</u>		275	-0.076	286	-0.004	74	-0.377
<u>CURVE 45</u>		648	1.786	289	-0.049	290	-0.002	89	-0.352
234	-0.067	580	1.488	292	-0.016	298	0.003	102	-0.334
223	-0.079	460	1.260	298	0.003	<u>CURVE 53</u>		130	-0.299
<u>CURVE 46</u>		406	0.849	77	-0.560	5	-0.166	144	-0.277
274	-0.012	<u>CURVE 52</u>		298	0.005	79	-0.143	158	-0.254
295	0.000	49	-0.133	<u>CURVE 54</u>		301	0.002	172	-0.232
337	0.028	86	-0.112	20	-0.160	<u>CURVE 56*</u>		186	-0.207
393	0.043	92	-0.109	77	-0.146	20	-0.121	200	-0.182
463	0.097	102	-0.105	197	-0.078	120	-0.100	213	-0.154
507	0.118	108	-0.103	297	0.003	200	-0.057	227	-0.127
563	0.128	119	-0.098	<u>CURVE 57*</u>		297	0.002	241	-0.100
615	0.130	137	-0.091	20	-0.135	<u>CURVE 64*</u>		255	-0.077
<u>CURVE 65*</u>		147	-0.086	77	-0.063	77	-0.057	269	-0.053
<u>CURVE 66*</u>		154	-0.084	297	0.003	120	-0.052	283	-0.023
<u>CURVE 67*</u>		<u>CURVE 55</u>		<u>CURVE 56*</u>		200	-0.032	294	0.000
<u>CURVE 68*</u>		<u>CURVE 53</u>		<u>CURVE 54</u>		297	0.001	<u>CURVE 69*</u>	
<u>CURVE 69*</u>		<u>CURVE 54</u>		<u>CURVE 55</u>		17	-0.102	33	-0.101
<u>CURVE 70*</u>		<u>CURVE 55</u>		<u>CURVE 56*</u>		<u>CURVE 71*</u>		<u>CURVE 72*</u>	
<u>CURVE 71*</u>		<u>CURVE 56*</u>		<u>CURVE 57*</u>		<u>CURVE 73*</u>		<u>CURVE 74*</u>	
<u>CURVE 72*</u>		<u>CURVE 57*</u>		<u>CURVE 58*</u>		<u>CURVE 75*</u>		<u>CURVE 76*</u>	
<u>CURVE 73*</u>		<u>CURVE 58*</u>		<u>CURVE 59*</u>		<u>CURVE 77*</u>		<u>CURVE 78*</u>	
<u>CURVE 74*</u>		<u>CURVE 59*</u>		<u>CURVE 60*</u>		<u>CURVE 79*</u>		<u>CURVE 80*</u>	
<u>CURVE 75*</u>		<u>CURVE 60*</u>		<u>CURVE 61*</u>		<u>CURVE 81*</u>		<u>CURVE 82*</u>	
<u>CURVE 76*</u>		<u>CURVE 61*</u>		<u>CURVE 62*</u>		<u>CURVE 83*</u>		<u>CURVE 84*</u>	
<u>CURVE 77*</u>		<u>CURVE 62*</u>		<u>CURVE 63*</u>		<u>CURVE 85*</u>		<u>CURVE 86*</u>	
<u>CURVE 78*</u>		<u>CURVE 63*</u>		<u>CURVE 64*</u>		<u>CURVE 87*</u>		<u>CURVE 88*</u>	
<u>CURVE 79*</u>		<u>CURVE 64*</u>		<u>CURVE 65*</u>		<u>CURVE 89*</u>		<u>CURVE 90*</u>	
<u>CURVE 80*</u>		<u>CURVE 65*</u>		<u>CURVE 66*</u>		<u>CURVE 91*</u>		<u>CURVE 92*</u>	
<u>CURVE 81*</u>		<u>CURVE 66*</u>		<u>CURVE 67*</u>		<u>CURVE 93*</u>		<u>CURVE 94*</u>	
<u>CURVE 82*</u>		<u>CURVE 67*</u>		<u>CURVE 68*</u>		<u>CURVE 95*</u>		<u>CURVE 96*</u>	
<u>CURVE 83*</u>		<u>CURVE 68*</u>		<u>CURVE 69*</u>		<u>CURVE 97*</u>		<u>CURVE 98*</u>	
<u>CURVE 84*</u>		<u>CURVE 69*</u>		<u>CURVE 70*</u>		<u>CURVE 99*</u>		<u>CURVE 100*</u>	
<u>CURVE 85*</u>		<u>CURVE 70*</u>		<u>CURVE 71*</u>		<u>CURVE 101*</u>		<u>CURVE 102*</u>	
<u>CURVE 86*</u>		<u>CURVE 71*</u>		<u>CURVE 72*</u>		<u>CURVE 103*</u>		<u>CURVE 104*</u>	
<u>CURVE 87*</u>		<u>CURVE 72*</u>		<u>CURVE 73*</u>		<u>CURVE 105*</u>		<u>CURVE 106*</u>	
<u>CURVE 88*</u>		<u>CURVE 73*</u>		<u>CURVE 74*</u>		<u>CURVE 107*</u>		<u>CURVE 108*</u>	
<u>CURVE 89*</u>		<u>CURVE 74*</u>		<u>CURVE 75*</u>		<u>CURVE 109*</u>		<u>CURVE 110*</u>	
<u>CURVE 90*</u>		<u>CURVE 75*</u>		<u>CURVE 76*</u>		<u>CURVE 111*</u>		<u>CURVE 112*</u>	
<u>CURVE 91*</u>		<u>CURVE 76*</u>		<u>CURVE 77*</u>		<u>CURVE 113*</u>		<u>CURVE 114*</u>	
<u>CURVE 92*</u>		<u>CURVE 77*</u>		<u>CURVE 78*</u>		<u>CURVE 115*</u>		<u>CURVE 116*</u>	
<u>CURVE 93*</u>		<u>CURVE 78*</u>		<u>CURVE 79*</u>		<u>CURVE 117*</u>		<u>CURVE 118*</u>	
<u>CURVE 94*</u>		<u>CURVE 79*</u>		<u>CURVE 80*</u>		<u>CURVE 119*</u>		<u>CURVE 120*</u>	
<u>CURVE 95*</u>		<u>CURVE 80*</u>		<u>CURVE 81*</u>		<u>CURVE 121*</u>		<u>CURVE 122*</u>	
<u>CURVE 96*</u>		<u>CURVE 81*</u>		<u>CURVE 82*</u>		<u>CURVE 123*</u>		<u>CURVE 124*</u>	
<u>CURVE 97*</u>		<u>CURVE 82*</u>		<u>CURVE 83*</u>		<u>CURVE 125*</u>		<u>CURVE 126*</u>	
<u>CURVE 98*</u>		<u>CURVE 83*</u>		<u>CURVE 84*</u>		<u>CURVE 127*</u>		<u>CURVE 128*</u>	
<u>CURVE 99*</u>		<u>CURVE 84*</u>		<u>CURVE 85*</u>		<u>CURVE 129*</u>		<u>CURVE 130*</u>	
<u>CURVE 100*</u>		<u>CURVE 85*</u>		<u>CURVE 86*</u>		<u>CURVE 131*</u>		<u>CURVE 132*</u>	
<u>CURVE 101*</u>		<u>CURVE 86*</u>		<u>CURVE 87*</u>		<u>CURVE 133*</u>		<u>CURVE 134*</u>	
<u>CURVE 102*</u>		<u>CURVE 87*</u>		<u>CURVE 88*</u>		<u>CURVE 135*</u>		<u>CURVE 136*</u>	
<u>CURVE 103*</u>		<u>CURVE 88*</u>		<u>CURVE 89*</u>		<u>CURVE 137*</u>		<u>CURVE 138*</u>	
<u>CURVE 104*</u>		<u>CURVE 89*</u>		<u>CURVE 90*</u>		<u>CURVE 139*</u>		<u>CURVE 140*</u>	
<u>CURVE 105*</u>		<u>CURVE 90*</u>		<u>CURVE 91*</u>		<u>CURVE 141*</u>		<u>CURVE 142*</u>	
<u>CURVE 106*</u>		<u>CURVE 91*</u>		<u>CURVE 92*</u>		<u>CURVE 143*</u>		<u>CURVE 144*</u>	
<u>CURVE 107*</u>		<u>CURVE 92*</u>		<u>CURVE 93*</u>		<u>CURVE 145*</u>		<u>CURVE 146*</u>	
<u>CURVE 108*</u>		<u>CURVE 93*</u>		<u>CURVE 94*</u>		<u>CURVE 147*</u>		<u>CURVE 148*</u>	
<u>CURVE 109*</u>		<u>CURVE 94*</u>		<u>CURVE 95*</u>		<u>CURVE 149*</u>		<u>CURVE 150*</u>	
<u>CURVE 110*</u>		<u>CURVE 95*</u>		<u>CURVE 96*</u>		<u>CURVE 151*</u>		<u>CURVE 152*</u>	
<u>CURVE 111*</u>		<u>CURVE 96*</u>		<u>CURVE 97*</u>		<u>CURVE 153*</u>		<u>CURVE 154*</u>	
<u>CURVE 112*</u>		<u>CURVE 97*</u>		<u>CURVE 98*</u>		<u>CURVE 155*</u>		<u>CURVE 156*</u>	
<u>CURVE 113*</u>		<u>CURVE 98*</u>		<u>CURVE 99*</u>		<u>CURVE 157*</u>		<u>CURVE 158*</u>	
<u>CURVE 114*</u>		<u>CURVE 99*</u>		<u>CURVE 100*</u>		<u>CURVE 159*</u>		<u>CURVE 160*</u>	

TABLE 6-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GLASS FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 68 (cont.)*		CURVE 71*	
61	-0.096	411	0.232
89	-0.099	398	0.212
116	-0.078	385	0.186
144	-0.070	373	0.166
172	-0.058	360	0.142
200	-0.045	348	0.118
227	-0.034	335	0.092
255	-0.019	323	0.066
283	-0.005	310	0.038
294	0.000	298	0.006
		293	0.000
CURVE 69*		CURVE 72*	
17	-0.787	293	0.000
33	-0.778	298	0.001
47	-0.769	310	0.002
61	-0.755	323	0.004
74	-0.742	335	0.005
89	-0.728	348	0.009
102	-0.707	360	0.012
116	-0.684	373	0.015
130	-0.658	385	0.019
144	-0.623	398	0.023
158	-0.585	399	0.025
172	-0.547		
186	-0.503	CURVE 73*	
200	-0.454	399	0.025
213	-0.400	398	0.025
227	-0.344	385	0.023
241	-0.278	373	0.020
255	-0.213	360	0.016
269	-0.130	348	0.012
283	-0.047	335	0.010
294	0.000	323	0.006
		310	0.003
CURVE 70*		298	0.001
293	0.000	293	0.000
298	0.006		
310	0.024		
323	0.044		
335	0.064		
348	0.088		
360	0.110		
373	0.140		
385	0.170		
398	0.204		
411	0.232		

* Not shown in figure.

e. Thermal Diffusivity

There is only one set of data available for the thermal diffusivity of glass fiber epoxy composite. This data set is tabulated in Table 6-11 and the information on specimen specification and measurement condition is given in Table 6-10.

The only available data set covers a narrow temperature range and the information on specimen characterization is too scarce. Therefore, no recommended values are given. The calculation of the thermal diffusivity from the tabulated values of thermal conductivity, specific heat, and density has not been carried out because the thermal diffusivity of a composite is not a well-defined quantity and because the values of the other properties are not for the very same material.

TABLE 6-10. MEASUREMENT INFORMATION ON THE THERMAL DIFFUSIVITY OF GLASS FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	132 Ogawa, K. and Noguchi, Y.	1968		300-422	LE-61N	Epoxy resin reinforced by nonalkaline glass cloth; 95 x 65 x 0.99 mm; density 1.76 g cm ⁻³ ; measured by infrared radiation method.

TABLE 6-11. EXPERIMENTAL DATA ON THE THERMAL DIFFUSIVITY OF GLASS FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Diffusivity, α , cm² s⁻¹]

T	α
CURVE 1*	
300	0.001775
334	0.001673
377	0.001502
422	0.001336

* No figure given.

3.7. Graphite Fiber Epoxy Composite

The graphite fibers used in the composites are made by the carbonization of organic filaments. The filaments most often used are made from polyacrylonitrile (PAN), although rayon and acrylic fibers have been used to a limited extent. The mechanical properties of graphite fiber depend on the temperature at which the carbonization process takes place. Carbonization at a temperature in the range 2800–3300 K results in fibers with high elastic modulus but relatively low tensile strength and at a temperature in the range 1800–2300 K yields fibers of the greatest tensile strength but only moderate modulus of elasticity. The density of the fibers varies from 1.74 to 1.94 g cm⁻³ depending on the carbonization temperatures used. The filaments are normally produced in untwisted, loose bundles or tows, consisting of ten thousand fibers.

Modified epoxy resins developed specifically for use in composites with graphite fibers are available commercially. These are thermosetting resins used for low pressure laminating and normally cannot be used in continuous service above about 450 K, although intermittent service at a higher temperature up to 490 K is possible. Many of the various epoxy resins used as matrix constituents of composites are proprietary formulations, the exact chemical compositions of which are not available.

For aerospace design, graphite fiber epoxy composites are generally supplied by the manufacturer as preregs. These are tapes or broadgoods consisting of graphite fibers impregnated with epoxy resin matrix and have only been partially cured and consequently have a limited shelf life and require special storage facilities. The preregs are used in the fabrication of laminates whose layer orientations are tailored to match individual design requirements. Consequently, large numbers of individually different cross-ply laminates are likely to be encountered, each of which has distinctive properties and characteristics, and hence must be distinctly identified whenever it is to be associated with specific quantitative data.

a. Thermal Conductivity

There are twenty-two sets of data available for the thermal conductivity of graphite fiber epoxy composites. The experimental data are tabulated in Table 7-3 and shown partially in Figure 7-1. The information on specimen characterization and measurement condition is given in Table 7-2. Most of the data are for composites with epoxy content of around 50 volume percent. The variation in the reported thermal conductivity values is quite substantial. Furthermore, the data by Gile [116] (curves 1 and 2) and by Hertz et al. [117] (curve 19-22) show different temperature dependences. The provisional

values tabulated in Table 7-1 and shown in Figure 7-1 are for a composite with 50 volume percent epoxy content. These values are based on the data of Knibbs et al. [146] (curves 7-18) and of Hertz et al. [117] (curves 19-22). Their uncertainty is estimated to be $\pm 25\%$.

TABLE 7-1. PROVISIONAL THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Thermal Conductivity, k, $\text{W cm}^{-1} \text{K}^{-1}$]

T	k	
	50 volume percent epoxy	
	a	b
50	0.039	0.0032
100	0.057	0.0046
150	0.073	0.0058
200	0.087	0.0068
250	0.099	0.0078
273	0.105	0.0082
300	0.111	0.0087
350	0.122	0.0096
400	0.130	0.0105

a Heat flow parallel to fiber direction.

b Heat flow perpendicular to fiber direction.

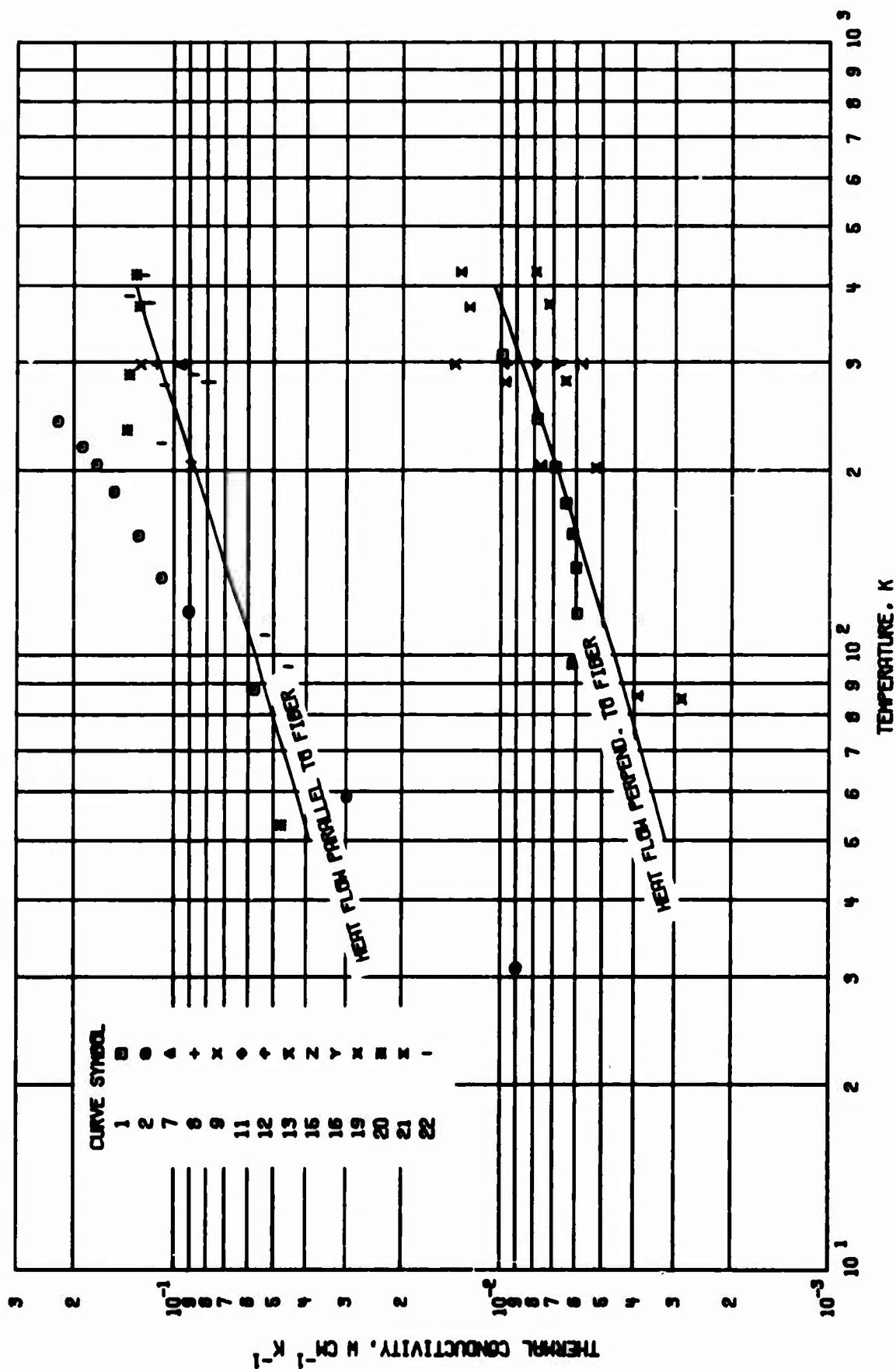


FIGURE 7-1. THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITES.

TABLE 7-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITES

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1 116	Gille, J.P.	1969	L	97-309	5	60" Thornel 50" graphite fibers bonded with Polaris epoxy resin; cylindrical shell specimen 1.005 in. I.D., 1.137 in. O.D., and 0.635 in. in effective length; heat flow perpendicular to fibers; data taken from smooth curve.
2 116	Gille, J.P.	1969	L	31-241	6	60" Thornel 50" graphite fibers bonded with Polaris epoxy resin; cylindrical shell specimen 0.998 in. I.D., 1.114 in. O.D., and 1.130 in. in effective length; heat flow parallel to fibers; data taken from smooth curve.
3* 146	Knibbe, R.H., Baker, D.J., and Rhodes, G.	1971	C	298		40 v/o surface treated Type I high modulus carbon fibers bonded with epoxy resin; 10 x 0.9 x 0.9 cm; molded; density 1.38 g cm ⁻³ ; electrical resistivity 2.19 mΩ cm; heat flow along fiber direction; Armco iron used as comparative material; reported error ± 5%.
4* 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.48 g cm ⁻³ , and electrical resistivity 1.90 mΩ cm.
5* 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.57 g cm ⁻³ , and electrical resistivity 1.51 mΩ cm.
6* 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.47 g cm ⁻³ , and electrical resistivity 1.80 mΩ cm.
7 146	Knibbe, R.H., et al.	1971	C	298		40 v/o surface treated Type II high strength carbon fibers bonded by epoxy resin; 10 x 0.9 x 0.9 cm; molded; density 1.30 g cm ⁻³ ; electrical resistivity 3.95 mΩ cm; heat flow along fiber direction; Armco iron used as comparative material; reported error ± 5%.
8 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.40 g cm ⁻³ , and electrical resistivity 2.88 mΩ cm.
9 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.44 g cm ⁻³ , and electrical resistivity 2.42 mΩ cm.
10* 146	Knibbe, R.H., et al.	1971	C	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.41 g cm ⁻³ , and electrical resistivity 2.90 mΩ cm.
11 146	Knibbe, R.H., et al.	1971	L	298		40 v/o surface treated Type I high modulus carbon fibers bonded by epoxy resin; 5 cm disc specimen; molded; density 1.38 g cm ⁻³ ; electrical resistivity 435 mΩ cm; heat flow perpendicular to fibers; reported error ± 20%.
12 146	Knibbe, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.48 g cm ⁻³ , and electrical resistivity 270 mΩ cm.
13 146	Knibbe, R.H., et al.	1971	L	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.57 g cm ⁻³ , and electrical resistivity 196 mΩ cm.
14* 146	Knibbe, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.47 g cm ⁻³ , and electrical resistivity 385 mΩ cm.
15 146	Knibbe, R.H., et al.	1971	L	298		40 v/o surface treated Type II high strength carbon fibers bonded by epoxy resin; 5 cm disc specimen; molded; density 1.30 g cm ⁻³ ; electrical resistivity 833 mΩ cm; heat flow perpendicular to fibers; reported error ± 20%.
16 146	Knibbe, R.H., et al.	1971	L	298		Similar to the above specimen except 50 v/o carbon fibers, density 1.40 g cm ⁻³ , and electrical resistivity 323 mΩ cm.

* Not shown in figure.

TABLE 7-2. MEASUREMENT INFORMATION ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17*	Knibbs, R. H., Baker, D. J., and Rhodes, G.	1971	L	298		Similar to the above specimen except 60 v/o carbon fibers, density 1.44 g cm ⁻³ , and electrical resistivity 172 mΩ cm.
18*	Knibbs, R. H., et al.	1971	L	298		Similar to the above specimen except 50 v/o untreated carbon fibers, density 1.41 g cm ⁻³ , and electrical resistivity 370 mΩ cm.
19	Hertz, J., Christian, J. L., and Varlas, M.	1972	L	85-422	HT-S/X-90	8 x 8 x 0.5 in. unidirection panel prepared by bonding HT-S graphite fibers with X-904 epoxy resin; heat flow perpendicular to fibers.
20	Hertz, J., et al.	1972	L	53-418	HT-S/X-904	Similar to the above specimen but heat flow parallel to fibers.
21	Hertz, J., et al.	1972	L	86-422	GY-70/HM-S/X-904	8 x 8 x 0.5 in. panel prepared by bonding GY-70 and HM-S graphite fibers with X-904 epoxy resin, with GY-70 and HM-S in alternate layers; panel orientation; [0° GY-70/90° HM-S/0° GY-70] 4T; heat flow perpendicular to fibers.
22	Hertz, J., et al.	1972	L	96-417	GY-70/HM-S/X-904	Similar to the above specimen but heat flow parallel to GY-70 fibers.

* Not shown in figure.

TABLE 7-3. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF GRAPHITE FIBER EPOXY COMPOSITE
[Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹]

T	k	T	k	T	k
<u>CURVE 1</u>		<u>CURVE 9</u>		<u>CURVE 20</u>	
97	0.00616	296	0.126	53	0.0476
117	0.00597			233	0.136
139	0.53602	<u>CURVE 10*</u>		287	0.136
156	0.00618	296	0.117	371	0.127
177	0.00646			418	0.130
203	0.00694	<u>CURVE 11</u>		<u>CURVE 21</u>	
243	0.00796	296	0.0079	86	0.00392
309	0.00995			204	0.00767
<u>CURVE 2</u>		<u>CURVE 12</u>		279	0.00976
31	0.00900	296	0.0096	370	0.0125
59	0.0259	<u>CURVE 13</u>		422	0.0133
86	0.0573	296	0.0138	<u>CURVE 22</u>	
116	0.0909			96	0.0454
134	0.109	<u>CURVE 14*</u>		108	0.0532
167	0.128	296	0.0088	207	0.0896
185	0.151	<u>CURVE 15</u>		222	0.109
205	0.171	296	0.0058	276	0.107
219	0.189	<u>CURVE 16</u>		279	0.0779
241	0.225	296	0.0067	279	0.0612
<u>CURVE 3*</u>		<u>CURVE 17*</u>		287	0.0878
296	0.393	296	0.0071	376	0.118
<u>CURVE 4*</u>		<u>CURVE 18*</u>		386	0.136
296	0.511	296	0.0067	417	0.123
<u>CURVE 5*</u>		<u>CURVE 19</u>			
296	0.649	85	0.00296		
<u>CURVE 6*</u>		202	0.00524		
296	0.661	280	0.00646		
<u>CURVE 7</u>		373	0.00724		
296	0.096	422	0.00792		
<u>CURVE 8</u>					
296	0.113				

* Not shown in figure.

b. Specific Heat

There are five sets of experimental data available for the specific heat of graphite fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 7-5. The experimental data are tabulated in Table 7-6 and partially shown in Figure 7-2. These data sets cover the following types of composites:

HT-S/X-904 (curves 1, 4, 5),
GY-70/X-904 (curve 2), and
GY-70/HM-S/X-904 (curve 3).

The provisional values generated as discussed in the following sections are for well cured and thermally stable composites. The resin content of each composite is given together with the specific heat values.

HTS/X-904 Composite

The provisional values tabulated in Table 7-4 and shown in Figure 7-2 are based on the measurements of Hertz, Christian, and Varlas [117] (curve 1). These values are considered accurate to about $\pm 10\%$.

GY-70/X-904 Composite

The provisional values tabulated in Table 7-4 and shown in Figure 7-2 are based on the measurements of Hertz, Christian, and Varlas [117] (curve 2). These values are considered accurate to about $\pm 10\%$.

TABLE 7-4. PROVISIONAL SPECIFIC HEAT OF GRAPHITE FIBER EPOXY COMPOSITE

[Temperature, T, K; Specific Heat, C_p , cal g⁻¹ K⁻¹]

T	C_p	
	GY-70/25 percent X-904	HT-S/28 percent X-904
100	0.082	0.079
150	0.118	0.117
200	0.152	0.155
250	0.186	0.192
273.15	0.202	0.208
293	0.214	0.222
300	0.219	0.228
350	0.252	0.263
400	0.284	0.297
450	0.315	0.329

TABLE 7-5. MEASUREMENT INFORMATION ON THE SPECIFIC HEAT OF GRAPHITE EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	Hertz, J., Christian, J. L., and Varian, M.	1972		89-450	Panel OC16-C3	HT-S/X-904 composite; specific gravity 1.56; resin content 28 percent.
2	Hertz, J., et al.	1972		89-450	Panel OC15-1-C2	GY-70/X-904 composite; specific gravity 1.706; resin content 24.8 percent.
3	Hertz, J., et al.	1972		89-450	Panel OC15-1-CC2	GY-70/HM-S/X-904 composite.
4*	Hertz, J., et al.	1972		82-450	1A-39-1	HT-S/X-904 composite.
5*	Hertz, J., et al.	1972		83-450	1A-39-1	Similar to the above specimen; water boiled for 24 hr.

TABLE 7-6. EXPERIMENTAL DATA ON THE SPECIFIC HEAT OF GRAPHITE FIBER EPOXY

[Temperature, T, K; Specific Heat, C_p , cal g ⁻¹ K ⁻¹]			
T	C_p	T	C_p
CURVE 1			
89	0.071	283	0.219
118	0.090	311	0.239
201	0.156	339	0.261
285	0.234	366	0.282
395	0.298	394	0.304
450	0.327	422	0.324
		450	0.344
CURVE 2			
89	0.076	CURVE 5*	
118	0.081	83	0.064
201	0.165	89	0.069
285	0.215	116	0.091
395	0.278	144	0.111
450	0.319	172	0.133
		200	0.153
		228	0.176
		255	0.196
CURVE 3			
89	0.066	CURVE 4 (cont.)*	
118	0.092	283	0.219
201	0.135	311	0.239
285	0.203	339	0.261
395	0.293	366	0.282
450	0.335	394	0.304
		422	0.324
		450	0.344
CURVE 4 *			
82	0.065	CURVE 5 (cont.)*	
89	0.070	255	0.197
116	0.093	283	0.218
144	0.113	311	0.239
172	0.134	339	0.262
200	0.155	366	0.282
228	0.176	394	0.303
255	0.196	422	0.323
		450	0.344

* Not shown in figure.

c. Heat of Fusion

No experimental data for the heat of fusion of graphite fiber epoxy composites were located in the literature. Most of the epoxy resins in their pure state are liquid above room temperature. The choices of a specific resin, a specific curing agent and curing mechanism are based on the considerations such as end use, curing conditions, cost, and the specific properties desired in the cured resin. The softening point of cured epoxy resin is near 450 K. No experimental data for the heat of fusion/softening of cured epoxy resin and for the heat of fusion of graphite were located in the literature. Graphite sublimates without melting at atmospheric pressure. Leidler, Krikorian, and Young [147] reported a value of 2500 cal g^{-1} for the heat of fusion of carbon at the triple point, 4600–4800 K and 48000 atm.

d. Thermal Linear Expansion

There are 154 sets of experimental data available for the thermal linear expansion of graphite fiber epoxy composites. The information on the specimen characterization and measurement condition for each of the data sets is given in Table 7-8. The experimental data are tabulated in Table 7-9 and partially shown in Figures 7-3A through 7-3E. These data sets are for unidirectional, cross-plyed, angle-plyed, orthotropic, and pseudo-isotropic laminates and cover the following types of composites:

Courtaulds HMS/Hercules 3002 epoxy (curves 3-11),
 Courtaulds HTS/ERLA 4617 epoxy (curves 92-94),
 Courtaulds HTS/Faberite X-904 epoxy (curves 107-126 and 151-154),
 Modmor I/ELRB 4617 epoxy (curves 104-106),
 Modmor II/Narmco 5206 epoxy (curves 12-17),
 GY-70/CRC 350A epoxy (curves 18-37),
 GY-70/Faberite X-904 epoxy (curves 95-98 and 127-137),
 GY-70/HMS/Faberite X-904 epoxy (curves 139-150),
 Thornel-25/Epon 815 epoxy (curves 60-63),
 Thornel-50/Epon 815 epoxy (curves 56-59),
 Thornel-75/Epon 815 epoxy (curves 52-55),
 Thornel-75S/ELRB 4617 epoxy (curves 101-103),
 Hercules HTS/Bloomington BP-907 epoxy (curves 65-68),
 Hercules HTS/Hercules 3002 epoxy (curves 69-81),
 Hercules HMS/Hercules 3002 epoxy (curves 82-89), and
 Hercules HMS/Bloomington BP-907 epoxy (curves 90 and 91).

Although several data sets are available for each type of composites, it is practically impossible from the available limited information to separate out the contributions of individual factors affecting the thermal expansion of composites. These factors include the type of fiber used, namely high modulus or high tensile strength, type of epoxy, fiber to epoxy ratio, curing process, and tendency of graphite fiber epoxy composite to absorb moisture. Most of the data sets do not show a reasonably stable thermal expansion behavior after one or two thermal cycles. Nakamura and Larsen [119] and Freeman and Campbell [148] from their extensive investigations have attributed this unstable expansion behavior to the absorption of moisture by the composite material. Thus the variation of thermal expansion from material to material may be due to one of the above reasons, the absorbed moisture being a major factor. A knowledge of the exact nature of these effects is required by the designer when these advanced

materials are used in structural applications under various environmental conditions. For these and other reasons, it is practically impossible to derive the most probable values which can be applied to composites in general.

The thermal expansion behavior of graphite fiber epoxy composites can be summarized as follows. The high modulus graphite fiber/epoxy composite has slightly lower thermal expansion than the high tensile strength graphite fiber/epoxy composite. The experimental results for the complex construction composites indicate that it is feasible to tailor the laminate orientations, fiber modulus, and fiber volume in a manner that will provide a structure with exceptional two dimensional thermal stability (i.e., low expansion) over a wide temperature range. The phenomenon of unstable expansion behavior relates to the absorption of moisture by fiber reinforced epoxy composites is significant.

The provisional thermal expansion values generated as discussed in the following sections are for the moisture-free composite and are based mainly on the data for stable thermal cycle for a given composite. The values are given for unidirectional and pseudo-isotropic laminates along fiber orientation and thickness direction. The thermal expansions of composites with high modulus graphite fiber and with high tensile strength graphite fiber are treated separately below.

High Modulus Graphite Fiber Epoxy Composite

(1) Unidirectional Fiber Orientation - Longitudinal

The provisional values tabulated in Table 7-7 and shown in Figure 7-3A are derived primarily from the measurements of Nakamura and Larsen [119] (curves 3-6), and of Freeman and Campbell [148] (curves 84, 85, and 90). Thermal expansion data of Kalnin [145] (curves 34 and 35) and of Freeman and Campbell [148] (curve 82) show unusually high contraction at temperatures above 293 K, and this may be due to the absorbed moisture by their composite specimens. The provisional values are for cured and moisture-free composite with high-modulus unidirectional graphite fibers (fiber modulus 50 to 70 x 10⁶ psi). The modulus of epoxy is 0.5 to 0.7 x 10⁶ psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber orientation direction. The uncertainty of the values is within ±20%.

(2) Unidirectional Fiber Orientation - Transverse

The provisional values tabulated in Table 7-7 and shown in Figure 7-3B are derived primarily from the measurements of Nakamura and Larsen [119] (curves 7-10),

Kalnín [145] (curves 36 and 37), Knibbs and Morris [149] (curve 44), Freeman and Campbell [148] (curves 83, 86, and 91), and of Goggin [150] (curves 103 and 106). These values are for cured and moisture-free composite with high-modulus unidirectional graphite fibers (fiber modulus 50 to 70×10^6 psi). The fiber content is 50-60 volume percent, the epoxy modulus is 0.5 to 0.7×10^6 psi, and the thermal expansion is along the fiber thickness direction. The uncertainty of the values is within $\pm 20\%$.

(3) Pseudo-Isotropic Fiber Orientation - Along Fiber Plane

The provisional values tabulated in Table 7-7 and shown in Figure 7-3C are derived primarily from the measurements of Nakamura and Larsen [119] (curve 11), Kalnín [145] (curves 18 and 19), and of Freund [151] (curve 95). Thermal expansion data of Freeman and Campbell [148] (curve 87) are considerably higher which may be due to the variation in the fiber orientation and experimental condition. The values are for cured and moisture-free composite with high-modulus pseudo-isotropically oriented graphite fibers (fiber modulus 50 to 70×10^6 psi). The epoxy modulus is 0.5 to 0.7×10^6 psi, the fiber content is about 50 volume percent, and the thermal expansion is along the fiber plane. The uncertainty of the values is within $\pm 20\%$.

High Tensile Strength Graphite Fiber Epoxy Composite

(1) Unidirectional Fiber Orientation - Longitudinal

The provisional values tabulated in Table 7-7 and shown in Figure 7-3D are derived from the measurements of Freeman and Campbell [148] (curves 69 and 70). Thermal expansion data of Nakamura and Larsen [119] (curve 16) and of Freeman and Campbell [148] (curve 65) show unusually low contraction at temperatures above 293 K, possibly due to absorbed moisture. The values are for cured and moisture-free composite with high-tensile-strength unidirectional graphite fibers (fiber modulus 30 to 40×10^6 psi). The epoxy modulus is 0.5 to 0.7×10^6 psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber orientation direction. The uncertainty of the values is within $\pm 25\%$.

(2) Unidirectional Fiber Orientation - Transverse

The provisional values tabulated in Table 7-7 and shown in Figure 7-3E are based on the measurements of Nakamura and Larsen [119] (curves 13-15), Knibbs and Morris [149] (curve 51), and of Freeman and Campbell [148] (curves 66, 68, and 72-74). These values are for cured and moisture-free composite with high-tensile-strength unidirectional graphite fibers (fiber modulus 30 to 40×10^6 psi). The epoxy modulus is

0.5 to 0.7×10^6 psi, the fiber content is 50-60 volume percent, and the thermal expansion is along the fiber thickness direction. The uncertainty of the values is within $\pm 25\%$.

(3) Pseudo-Isotropic Fiber Orientation - Along Fiber Plane

The provisional values tabulated in Table 7-7 and shown in Figure 7-3C are based on the measurements of Nakamura and Larsen [119] (curve 17). These values are for cured and moisture-free composite with high-tensile-strength pseudo-isotropically oriented graphite fibers (fiber modulus 30 to 40×10^6 psi). The epoxy modulus is 0.5 to 0.7×10^6 psi, the fiber content is 50 volume percent, and the thermal expansion is along the fiber plane. The uncertainty of the values is within $\pm 25\%$.

The values of the instantaneous coefficient of thermal linear expansion, α , for the above composites are obtained by differentiation of empirical equations which are used to fit the provisional thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the expansion curve. The uncertainty of these values is about $\pm 25\%$.

**TABLE 7-7. PROVISIONAL THERMAL LINEAR EXPANSION OF
GRAPHITE FIBER EPOXY COMPOSITES**

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; Coefficient of Expansion, α , 10^{-6} K^{-1}]

a. High Modulus Graphite Fiber Epoxy Composite

T	Unidirectional Fiber Orientation				Pseudo-Isotropic Fiber Orientation	
	Longitudinal		Transverse		Along Fiber Plane	
	$\Delta L/L_0$	α	$\Delta L/L_0$	α	$\Delta L/L_0$	α
75			-0.564	19.4		
80			-0.555	19.6		
90			-0.535	20.1		
100	0.0124	-0.8	-0.515	20.6		
150	0.0086	-0.7	-0.405	23.3		
200	0.0052	-0.6	-0.280	26.6		
250	0.0022	-0.6	-0.138	30.4	-0.0011	0.2
273.15	0.0010	-0.5	-0.066	32.3	-0.0006	0.3
293	0.0000	-0.5	0.000	34.0	0.0000	0.4
300	-0.0004	-0.5	0.024	34.6	0.0003	0.4
350	-0.0027	-0.4	0.209	39.4	0.0025	0.5
400	-0.0042	-0.3	0.419	44.7	0.0049	0.5
450	-0.0054	-0.2	0.656	50.4	0.0069	0.5

b. High Tensile Strength Graphite Fiber Epoxy Composite

75	0.0080	-0.4	-0.442	15.8		
80	0.0078	-0.4	-0.434	16.0		
90	0.0074	-0.4	-0.418	16.3		
100	0.0070	-0.4	-0.402	16.6		
150	0.0051	-0.4	-0.314	18.5		
200	0.0033	-0.4	-0.216	20.5		
250	0.0015	-0.4	-0.106	23.4	-0.0020	0.4
273.15	0.0007	-0.3	-0.050	24.8	-0.0010	0.5
293	0.0000	-0.3	0.000	26.1	0.0000	0.6
300	-0.0002	-0.3	0.018	26.5	0.0004	0.6
350	-0.0020	-0.3	0.160	30.0	0.0037	0.7
400	-0.0036	-0.3	0.319	33.9	0.0073	0.8
450	-0.0052	-0.3	0.500	38.2	0.0110	0.8

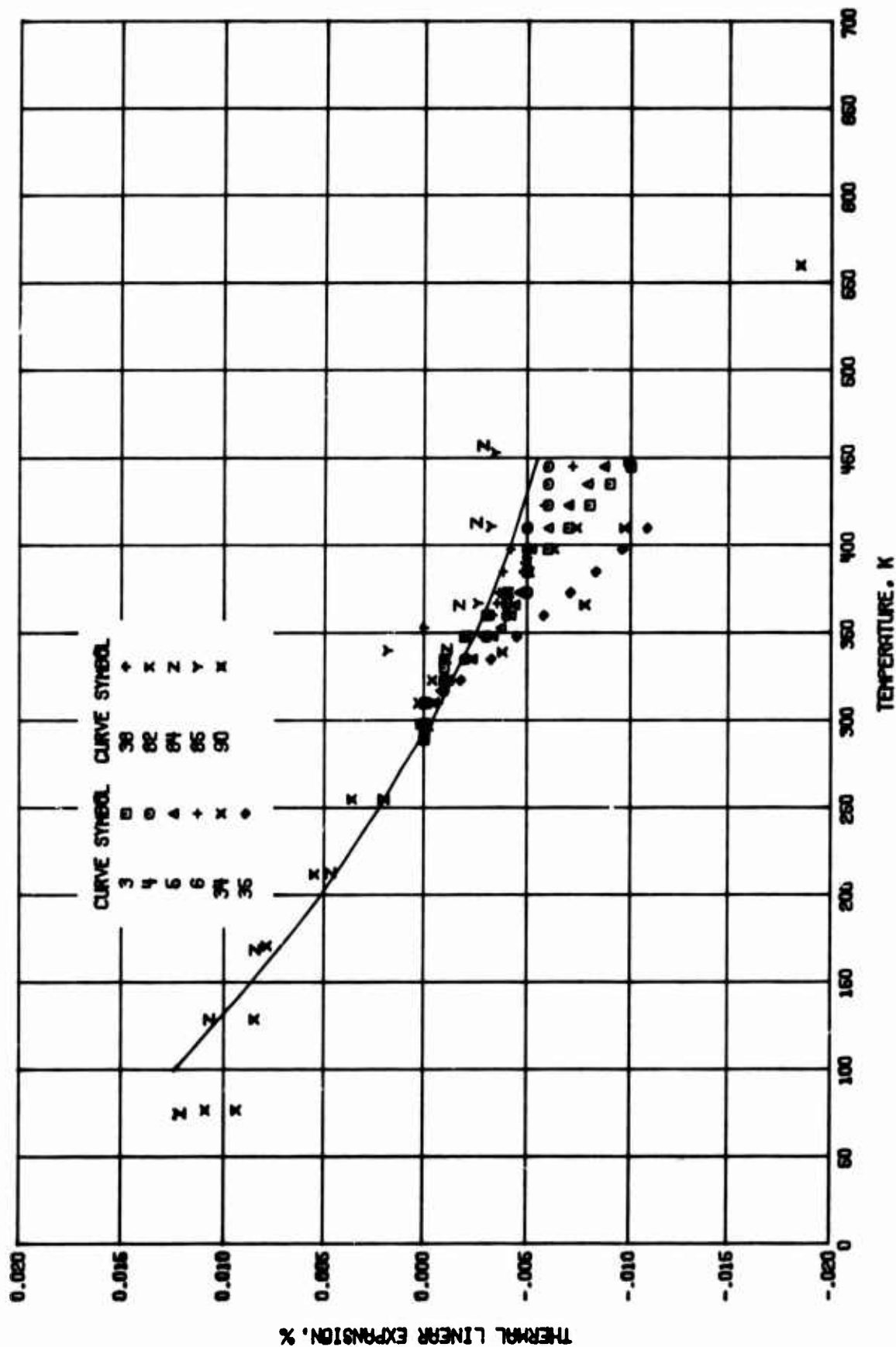


FIGURE 7-3A. LONGITUDINAL THERMAL LINEAR EXPANSION OF HIGH MODULUS GRAPHITE FIBER EPOXY COMPOSITES.

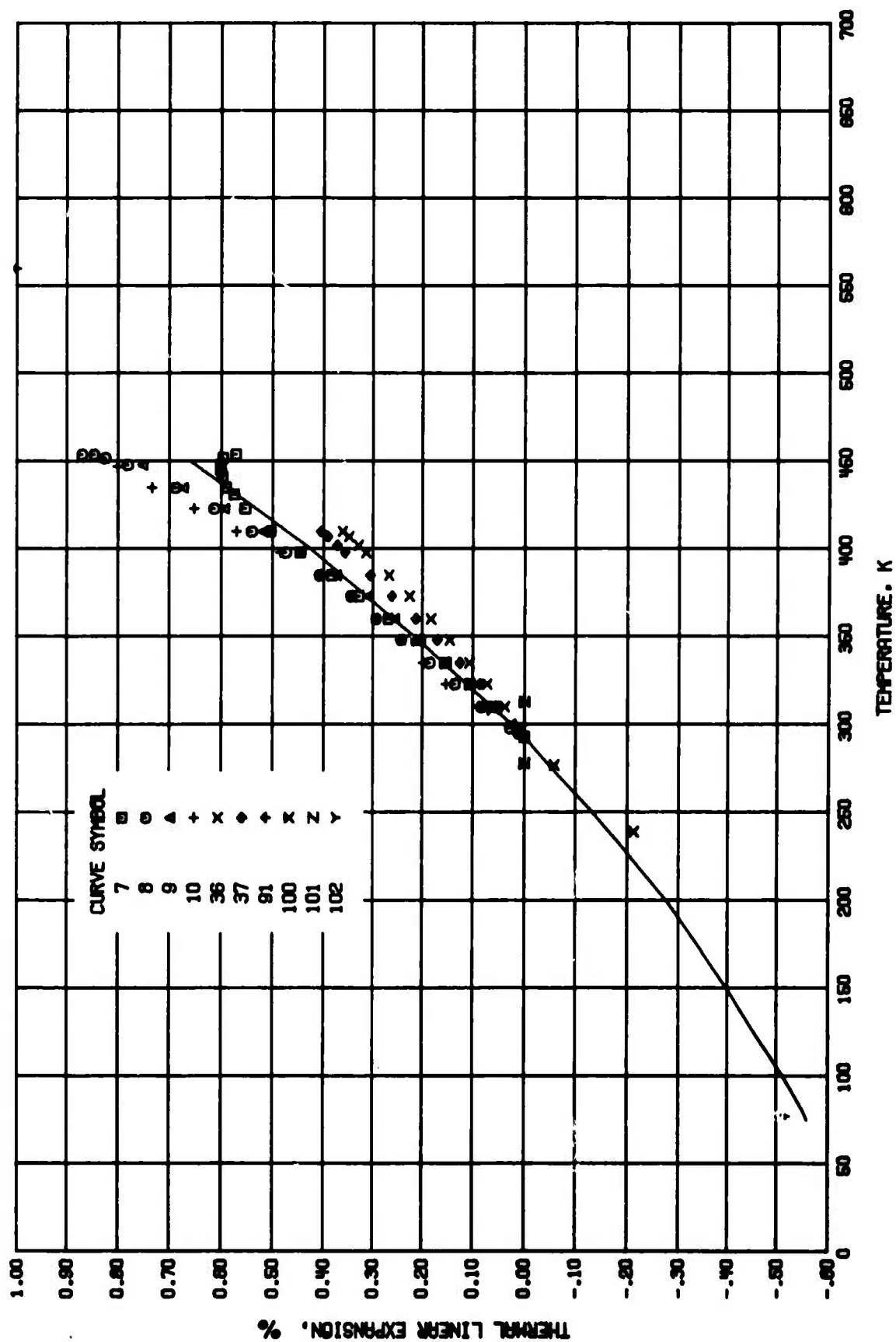


FIGURE 7-38. TRANSVERSE THERMAL LINEAR EXPANSION OF HIGH MODULUS GRAPHITE FIBER EPOXY COMPOSITES .

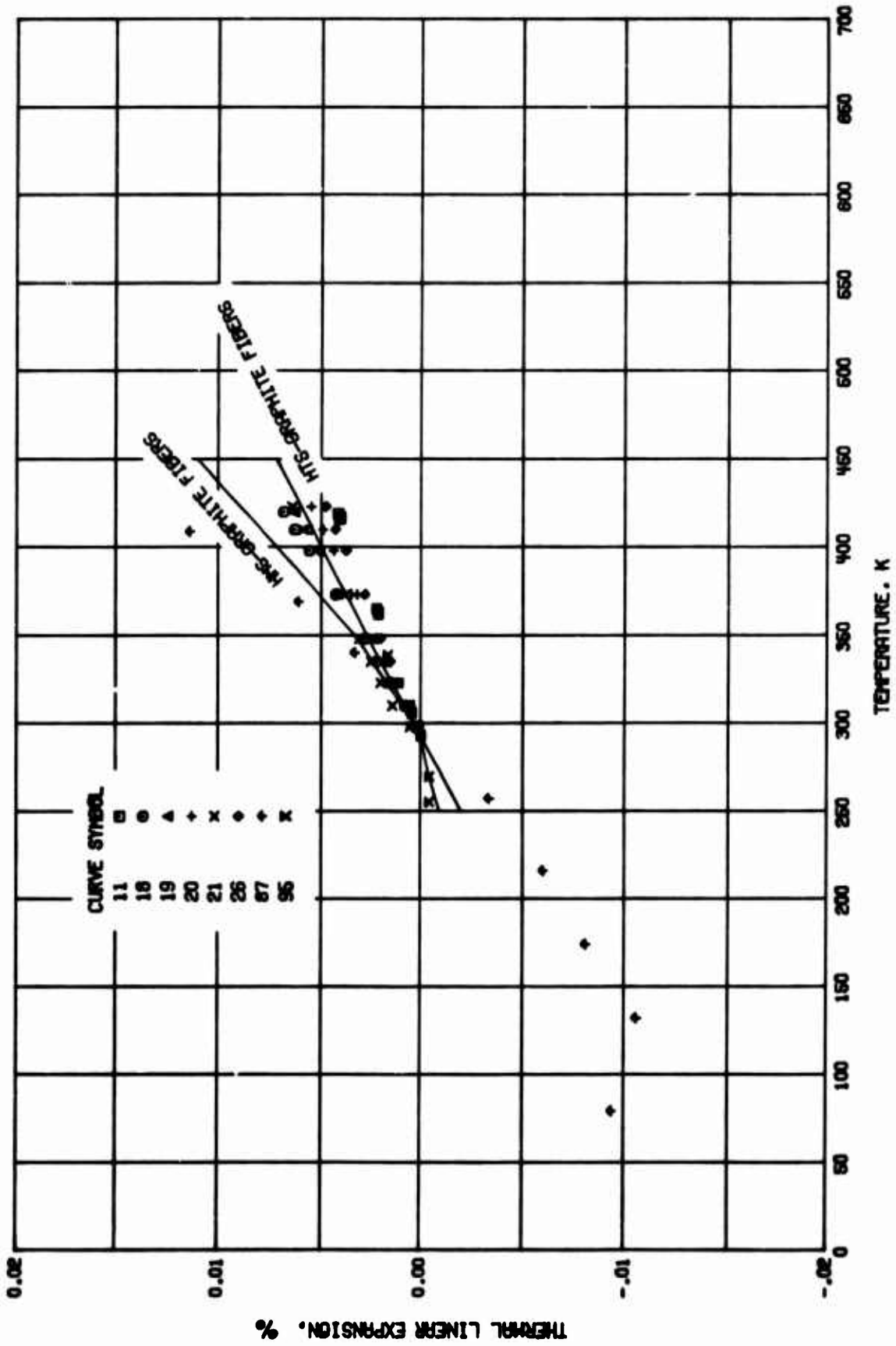


FIGURE 7-3C. THERMAL LINEAR EXPANSION OF PSEUDOISOTROPIC GRAPHITE FIBER EPOXY COMPOSITES .

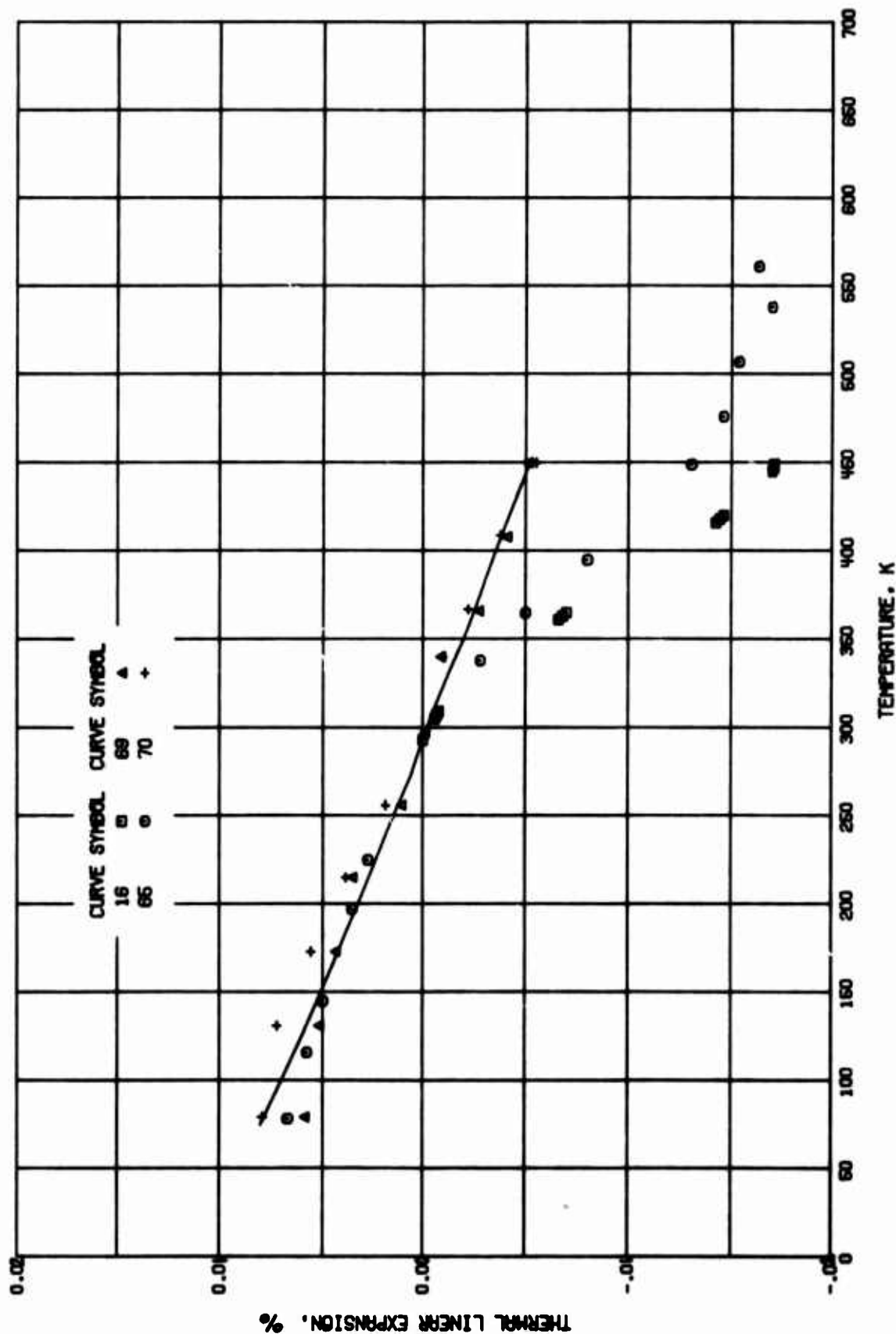


FIGURE 7-30. LONGITUDINAL THERMAL LINEAR EXPANSION OF HIGH STRENGTH GRAPHITE FIBER EPOXY COMPOSITES .

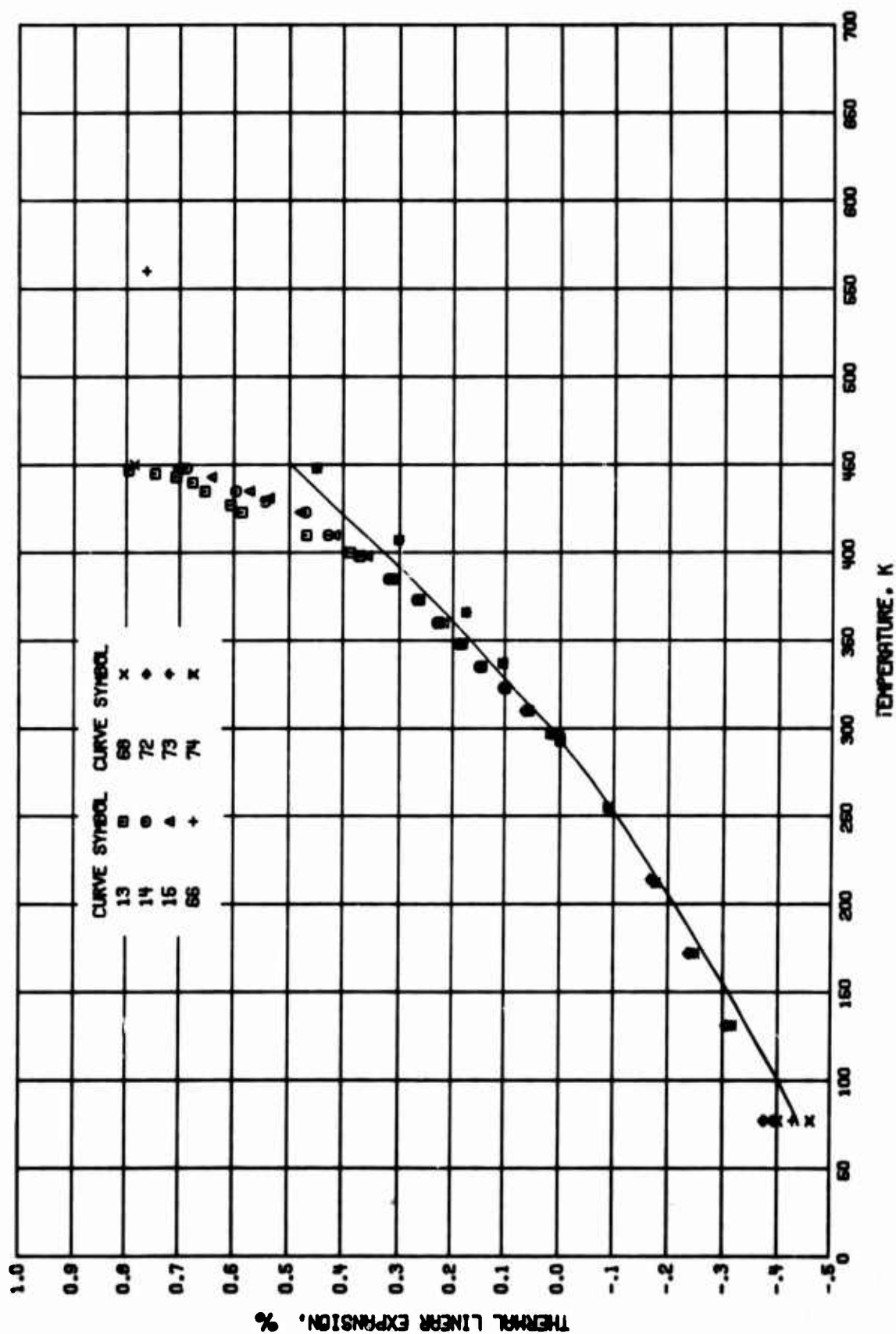


FIGURE 7-3E. TRANSVERSE THERMAL LINEAR EXPANSION OF HIGH STRENGTH GRAPHITE FIBER EPOXY COMPOSITES .

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	Prime, R. B., Barrall, II, E. M., Logan, J. A., and Duke, P. J.	1974		323	Pseudo-random Courtaulds HMS	High modulus graphite fibers/epoxy matrix; six plies (0 \pm 60) g; 45-50 volume % chopped fibers; orientation of composite is 0 deg with respect to surface fibers; measured using thermomechanical analysis technique.
2*	Prime, R. B., et al.	1974		323	Pseudo-random Courtaulds HMS	The above specimen except orientation of composite material is 90 deg with respect to surface fibers.
3	Nakamura, H. H. and Larsen, D. C.	1974	L	289-445	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm ⁻³ ; fiber tensile modulus 45 x 10 ⁴ psi; composite stiffness 27 x 10 ⁴ psi; six plies of 0 deg (longitudinal) fiber orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles, fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; expansion in the specimen (and specimens in curves thru 17) measured along length direction for three specimens of angle 0.5 x 2 in. laminate roughly 0.050 in. thick; specimen exhibited 0.1-0.3% weight loss; first heating cycle; significant shrinkage observed.
4	Nakamura, H. H. and Larsen, D. C.	1974	L	445-290	Courtaulds HMS/Hercules 3002 M	The above specimen; first cooling cycle; zero-point correction is 0.003%.
5	Nakamura, H. H. and Larsen, D. C.	1974	L	290-445	Courtaulds HMS/Hercules 3002 M	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.003%.
6	Nakamura, H. H. and Larsen, D. C.	1974	L	445-288	Courtaulds HMS/Hercules 3002 M	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.005%.
7	Nakamura, H. H. and Larsen, D. C.	1974	L	293-454	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm ⁻³ ; fiber tensile modulus 45 x 10 ⁴ psi; composite stiffness 27 x 10 ⁴ psi; eight plies of 90 deg (transverse) orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; first heating cycle; significant shrinkage observed; specimens exhibited weight loss of 0.1 to 0.3%; zero-point correction is 0.013%.
8	Nakamura, H. H. and Larsen, D. C.	1974	L	454-293	Courtaulds HMS/Hercules 3002 M	The above specimen; first cooling cycle; zero-point correction is 0.312%.
9	Nakamura, H. H. and Larsen, D. C.	1974	L	293-448	Courtaulds HMS/Hercules 3002 M	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.307%.
10	Nakamura, H. H. and Larsen, D. C.	1974	L	447-293	Courtaulds HMS/Hercules 3002 M	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.372%.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
11	Nakamura, H. H. and Larsen, D. C.	1974	L	293-447	Courtaulds HMS/Hercules 3002 M	High modulus graphite fiber system; density 1.6 g cm^{-3} ; fiber tensile modulus 45×10^4 psi; composite stiffness 27×10^4 psi; nine plies of balanced symmetric unidirectional-angle ply orientation designated [0/45/135/0/90] _s ; plies stacked in directions (0/+45/-45/0/90/0/-45/+45/0); individual ply thickness 5-8 mils; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
12*	Nakamura, H. H. and Larsen, D. C.	1974	L	293-447	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3} ; fiber modulus 38×10^4 psi; composite strength 161 ksi; eight plies of 90 deg (transverse) orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; first heating cycle; significant shrinkage observed; zero-point correction is 0.009%.
13	Nakamura, H. H. and Larsen, D. C.	1974	L	447-293	Modmor II/ Narmco 5206	The above specimen; first cooling cycle; zero-point correction is 0.485%.
14	Nakamura, H. H. and Larsen, D. C.	1974	L	293-448	Modmor II/ Narmco 5206	The above specimen except second heating cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.485%.
15	Nakamura, H. H. and Larsen, D. C.	1974	L	448-293	Modmor II/ Narmco 5206	The above specimen except second cooling cycle; more stable expansion behavior exhibited during this cycle; zero-point correction is 0.500%.
16	Nakamura, H. H. and Larsen, D. C.	1974	L	293-449	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3} ; fiber modulus 38×10^4 psi; composite strength 161 ksi; six plies of 0 deg (longitudinal) fiber orientation; reinforced epoxy laminates 5 to 7 mil diameter fiber bundles; fiber 50 volume %; autoclave process provided the final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
17*	Nakamura, H. H. and Larsen, D. C.	1974	L	293-420	Modmor II/ Narmco 5206	High strength graphite fiber system; density 1.5 g cm^{-3} ; fiber modulus 38×10^4 psi; composite strength 161 ksi; nine plies of balanced symmetric unidirectional-angle ply orientation designated [0/45/135/0/90] _s ; plies stacked in directions (0/+45/-45/0/90/0/-45/+45/0); individual ply thickness 5.8 mils; fiber 50 volume %; autoclave process provided final pressure and temperature cycles necessary to cure the resin; reported values are for second stable cycle.
18	Kahala, I. L.	1974	L	293-420	GY-70/350 A Laminate	Quasi-isotropic multidirectional laminates made by vacuum/pressure bagging of oriented layups of high modulus (75×10^4 psi) UD Cello R GY-70 graphite tape 7.5 cm wide, prepregged with CRC 350 A resin - a novolac base epoxy/anhydride system; eight plies [90, 45, 0, -45] _s ; fiber content 60 volume %; cure cycle of 6 hr at 450 K and external pressure of 75 psi; length of the specimen (and specimens in the curves thru 37) is 50 mm; to eliminate nonequilibrium thermal stresses the specimen (and specimens in curves thru 37) cycled 2-3 times between room temperature and 423 K prior to actual measurements; measurements in the principal laminate direction of 0 deg; heating cycle.
19	Kahala, I. L.	1974	L	420-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
20	Kahala, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 45 deg; heating cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
21	Kahina, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
22*	Kahina, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 90 deg; heating cycle.
23*	Kahina, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
24*	Kahina, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of -45 deg; heating cycle.
25*	Kahina, I. L.	1974	L	423-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
26	Kahina, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except twelve plies (+60, 0, -60) ₃ laminate; measurements in the principle laminate direction of 0 deg; average of heating and cooling.
27*	Kahina, I. L.	1974	L	293-421	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 30 deg; heating cycle.
28*	Kahina, I. L.	1974	L	421-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
29*	Kahina, I. L.	1974	L	293-424	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 45 deg; heating cycle.
30*	Kahina, I. L.	1974	L	424-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
31*	Kahina, I. L.	1974	L	293-424	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 60 deg; heating cycle.
32*	Kahina, I. L.	1974	L	424-293	GY-70/350 A Laminate	The above specimen except cooling cycle.
33*	Kahina, I. L.	1974	L	293-423	GY-70/350 A Laminate	The above specimen except measurements in the principal laminate direction of 90 deg.
34	Kahina, I. L.	1974	L	293-410	UD GY-70/350 A	Composites of density 1.68 g cm ⁻³ were made from prepregged GY-70 graphite yarn bundles by the "leaky" pressure molding technique in the form of bars 2.5 cm wide and 25-30 cm long; fiber content 60 ± 1 volume %; void content of < 3% neglected in the calculations; cured panels trimmed, jigged and cut to 0.65 cm strips along those directions in which expansion were to be measured; measurements along axial direction; heating cycle.
35	Kahina, I. L.	1974	L	410-293	UD GY-70/350 A	The above specimen except cooling cycle.
36	Kahina, I. L.	1974	L	293-410	UD GY-70/350 A	The above specimen except measurements along transverse direction; heating cycle.
37	Kahina, I. L.	1974	L	410-293	UD GY-70/350 A	The above specimen except cooling cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
38* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Composite made from high modulus carbon fibers and conventional epoxide resin using hardener, diamino diphenyl methane (D.D.M.); final fiber 50 volume %; 1.7 to 6 volume % voids, specimen of 8 x 1.1 x 0.9 cm was cut at an angle 0 deg to the lay of fibers.
39* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 10 deg to the lay of fibers.
40* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 20 deg to the lay of fibers.
41* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 30 deg to the lay of fibers.
42* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 45 deg to the lay of fibers.
43* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 65 deg to the lay of fibers.
44* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type I	Similar to the above specimen except specimen was cut at an angle 90 deg to the lay of fibers.
45* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Composite made from high strength carbon fibers and conventional epoxide resin using hardener diamino diphenyl methane (D.D.M.); final fiber 50 volume %, 1.7 to 6 volume % voids, specimen of 8 x 1.1 x 0.9 cm was cut at an angle 0 deg to the lay of fibers.
46* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 10 deg to the lay of fibers.
47* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 20 deg to the lay of fibers.
48* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 30 deg to the lay of fibers.
49* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 45 deg to the lay of fibers.
50* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 65 deg to the lay of fibers.
51* 149	Knibbs, R. H. and Morris, J. B.	1971	L	353-393	Type II	Similar to the above specimen except specimen was cut at an angle 90 deg to the lay of fibers.
52* 153	Daukays, R. J.	1973		243-303		Discontinuous graphite fiber modification of epoxy potting compound of density 1.19 g cm ⁻³ obtained by mixing chopped Thormal-75 (Union Carbide) continuous yarn (average modulus 83 x 10 ⁶ psi; tensile strength 330 ksi) with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen is 2 x 0.375 x 0.25 in.; average of two runs.
53* 153	Daukays, R. J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.22 g cm ⁻³ .

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy.
55*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.23 g cm^{-3} .
56*	Daukays, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.19 g cm^{-3} obtained by mixing chopped Thornel-50 (Union Carbide) continuous yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen $2 \times 0.375 \times 0.25 \text{ in.}$
57*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.19 g cm^{-3} .
58*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy; density 1.18 g cm^{-3} .
59*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.18 g cm^{-3} .
60*	Daukays, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.17 g cm^{-3} obtained by mixing chopped Thornel-25 (Union Carbide) continuous yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA), rectangular cross section of specimen $2 \times 0.375 \times 0.25 \text{ in.}$; average of two runs.
61*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 10 parts per hundred of epoxy; density 1.01 g cm^{-3} .
62*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 14 parts per hundred of epoxy; density 1.44 g cm^{-3} .
63*	Daukays, R.J.	1973		243-303		Similar to the above specimen except fiber content 16 parts per hundred of epoxy; density 1.19 g cm^{-3} .
64*	Daukays, R.J.	1973		243-303		Discontinuous graphite modification of epoxy potting compound of density 1.16 g cm^{-3} obtained by mixing chopped continuous yarn (designated as VYB-105-1/9 of lower modulus than Thornel yarn with epoxy (Epon 815) from Shell; fiber content 5 parts per hundred of epoxy, mixing time 25 min, cured at room temperature for 16 hr before experiments, curing agent diethylene triamine (DTA); rectangular cross section of specimen $2 \times 0.375 \times 0.25 \text{ in.}$
65	Freeman, W.T. and Campbell, M.D.	1972	L	70-561	Specimen 4 P13N-T	TRW P13N resin (modulus 0.55 Msi) reinforced with Hercules high tensile (modulus 36.6 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 57.6 volume %; void content 5.3%; specimen stored in dry helium at 297 K for 18 hr (pretest storage environment); shrinkage $1.07 \times 10^{-4} \%$ after first high temperature cycle; longitudinal lamina expansion.
66	Freeman, W.T. and Campbell, M.D.	1972	L	70-561	Specimen 5 P13N-T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 57 volume %; void content 5.8%; specimen stored in dry helium at 297 K for 18 hr; shrinkage $13.54 \times 10^{-4} \%$ after first high temperature cycle; transverse lamina expansion.
67*	Freeman, W.T. and Campbell, M.D.	1972	L	84-365	Specimen 6 BP907-T	Bloomingdale BP-907 resin (modulus 0.50 Msi) reinforced with Hercules high tensile (modulus 34.9 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 60.2 volume %; void content 0.4%; stored in dry helium at 297 K for 18 hr; shrinkage $0.13 \times 10^{-4} \%$ after first high temperature cycle; longitudinal lamina expansion.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
68	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 7 BP907-T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 60.2 volume %; void content 0.4%; specimen stored in dry helium at 297 K for 18 hr; shrinkage 15.88×10^{-4} % after first high temperature cycle; transverse lamina expansion.
69	Freeman, W. T. and Campbell, M. D.	1972	L	79-450	Specimen 8 3002T	Hercules 3002 resin (modulus 0.7 Msi) reinforced with Hercules high tensile (modulus 36.0 Msi) graphite fibers, fiber orientation 0 deg to the top ply; fiber 66.2 volume %; void content 0.0%; to assure constant fiber volume and thickness, small prepreg sheets were laminated with fiber orientation and press cured in the same mold; stored in dry helium at 297 K for 18 hr; shrinkage 1.02×10^{-4} % after first high temperature cycle; specimen cycled three times from 297 K to 450 K and final cycle from 297 K to 67 K.
70	Freeman, W. T. and Campbell, M. D.	1972	L	79-450	Specimen 9 3002T	Similar to the above specimen except shrinkage 0.28×10^{-4} % after first high temperature cycle.
71*	Freeman, W. T. and Campbell, M. D.	1972	S	227-367	Specimen 10 3002T	Similar to the above specimen except stored in 50% relative humidity at 297 K; shrinkage 0.04×10^{-4} % after first high temperature cycle.
72	Freeman, W. T. and Campbell, M. D.	1972	L	77-448	Specimen 11 3002T	Similar to the above specimen except fiber orientation 90 deg to the top ply; fiber 65.9 volume %; stored in dry helium at 297 K for 18 hr; cycled three times to 77 K and final to 450 K; shrinkage 3.31×10^{-4} % after first high temperature cycle; transverse lamina expansion.
73	Freeman, W. T. and Campbell, M. D.	1972	L	77-448	Specimen 12 3002T	Similar to the above specimen except stored in dry helium at 297 K for 48 hr; cycled three times to 450 K and final to 77 K; shrinkage 7.74×10^{-4} % after first high temperature cycle; transverse lamina expansion.
74	Freeman, W. T. and Campbell, M. D.	1972	L	77-448	Specimen 13 3002T	Similar to the above specimen except specimen stored in vacuum at 297 K for 24 hr; shrinkage 1.43×10^{-4} % after first high temperature cycle; transverse lamina expansion.
75*	Freeman, W. T. and Campbell, M. D.	1972	S	200-433	Specimen 14 3002T	Similar to the above specimen except stored in 50% relative humidity at 297 K; shrinkage 0.2×10^{-4} % after first high temperature cycle; transverse lamina expansion.
76*	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 15 3002T	Orthotropic laminates prepared from Hercules 3002 resin (modulus 0.70 Msi) with Hercules high tensile (modulus 36.0 Msi) graphite fibers, fiber orientation 0, ± 45 , 90 deg to the top ply, fiber 65.1 volume %; void content 0.0%; stored in dry helium at 297 K for 98 hr; to assure constant fiber volume and thickness, small prepreg sheets were laminated with fiber orientation and press cured in the same mold; shrinkage 1.27×10^{-4} % after first high temperature cycle.
77*	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 16 3002T	Similar to the above specimen except fiber orientation 0, 90 deg to the top ply; fiber 65.6 volume %, void content 0.0%; stored in dry helium at 297 K for 72 hr; shrinkage 0.56×10^{-4} % after first high temperature cycle.
78*	Freeman, W. T. and Campbell, M. D.	1972	S	297-450	Specimen 17 3002T	Similar to the above specimen; stored in 50% relative humidity at 297 K; shrinkage 0.31×10^{-4} % after first high temperature cycle.
79*	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 18 3002T	Similar to the above specimen except fiber orientation ± 30 deg to the top ply; fiber 65 volume %; specimen stored in dry helium at 297 K for 122 hr; shrinkage 0.41×10^{-4} % after first high temperature cycle.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
80*	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 19 3002T	Similar to the above specimen except fiber orientation ± 45 deg to the top ply; fiber 65.6 volume %; specimen stored in dry helium at 297 K for 146 hr; shrinkage 1.78×10^{-4} % after first high temperature cycle.
81*	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 20 3002T	Similar to the above specimen except fiber orientation ± 60 deg to the top ply; fiber 65.6 volume %; specimen stored in dry helium at 297 K for 170 hr; shrinkage 4.3×10^{-4} % after first high temperature cycle.
82	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 21 3002M	Hercules 3002 resin (modulus 0.70 Msi) reinforced with Hercules high modulus (57.2 Msi) graphite fibers; fiber orientation 0 deg to the top ply, fiber 56.3 volume %, void content 2.4%; stored in dry helium at 297 K for 18 hr; shrinkage 0.56×10^{-4} % after first high temperature cycle; longitudinal lamina expansion.
83*	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 22 3002M	Similar to the above specimen, except fiber orientation 90 deg to the top ply; fiber volume 56.3%, void content 2.4%; stored in dry helium at 297 K for 18 hr; shrinkage 2.83×10^{-4} % after first high temperature cycle.
84	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 23 3002M	Similar to the above specimen except fiber orientation 0 deg to the top ply; fiber 49.2 volume %, void content 2.8%; stored in air at 394 K for 40 hr; shrinkage 0.36×10^{-4} % after first high temperature cycle; longitudinal lamina expansion; first run.
85	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 23 3002M	Same as the above specimen; second run.
86*	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 24 3002M	Similar to the above specimen except fiber orientation 90 deg to the top ply; shrinkage 4.30×10^{-4} %.
87	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 25 3002M	Similar to the above specimen except fiber orientation of quasi-isotropic laminate 0 \pm 60 to the top ply; specimen machined along the unidirectional fiber lamina in the plate; fiber 48.6 volume %, void content 3.4%; stored in air at 394 K for 40 hr; shrinkage 0.43×10^{-4} %.
88*	Freeman, W. T. and Campbell, M. D.	1972	L	77-450	Specimen 26 3002M	Similar to the above specimen except specimen machined at 15 deg angle clockwise positive to the top unidirectional ply.
89*	Freeman, W. T. and Campbell, M. D.	1972	L	77-408	Specimen 27 3002M	Similar to the above specimen except specimen machined at 30 deg angle clockwise positive to the top unidirectional ply.
90	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 28 BP907M	Bloomingdale BP-907 resin (modulus 0.50 Msi) reinforced with Hercules high modulus (modulus 55.0 Msi) graphite fibers; fiber orientation 0 deg to the top ply; fiber 62.3 volume %; void content 0.0%; stored in desiccant at 297 K for 24 hr; shrinkage 0.10×10^{-4} % after first high temperature cycle; longitudinal lamina expansion.
91	Freeman, W. T. and Campbell, M. D.	1972	L	297-450	Specimen 29 BP970M	Similar to the above specimen except fiber orientation 90 deg to the top ply; shrinkage 3.49×10^{-4} % after first high temperature cycle; transverse lamina expansion.
92*	Pirgon, O., Wootenholm, G. H., and Yates, B.	1973	I			Specimen from test bars of 13 mm ² cross section, contains 50 volume % carbon fibers Courtaulds HTS carbon fibers, batch PTT 112/212 prepared from polyacrylonitril together with resin ERLA4617 batch B14 hardened with metaphenylene diamine; fibers were assembled in the form of 22 layers of 8 tows per layer; each tow contains 10 ⁴ fibers giving a total of 1.76×10^6 fibers over the cross section of the specimen; cut in a direction perpendicular to the fiber axis; measurements on the similar bar cut parallel to the fiber axis give widely scattered data, so these results were not tabulated.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
93*	Pirgon, O., Wostenholm, G. H., and Yates, B.	1973	I			Similar to the above specimen except specimen cut 45 deg to the fiber axis.
94*	Pirgon, O., et al.	1973	I			Similar to the above specimen except specimen cut perpendicular to the fiber axis.
95	Freund, N. P.	1974		255-338		Manufactured by GD/Convair, ultrahigh modulus Gr/Ep system composed of GY-70 graphite fibers by Celanese Corp., and X-904 epoxy resin by Faberite Corp.; pseudo isotropic lay ups with symmetric configuration (0/±45/90); measurements parallel to the outer most fiber orientation; average of 2 tests.
96*	Freund, N. P.	1974		255-338		Similar to the above specimen except measurements 90 deg to the outermost fiber orientation.
97*	Freund, N. P.	1974				Similar to the above specimen except measurements at an angle 45 deg to the outermost fiber orientation.
98*	Freund, N. P.	1974				Similar to the above specimen except measurements normal to surface.
99*	Keller, L. B. and Raech, H.	1974	L			Long fiber molding compound from Fiberite Corp; comprised of bundles of 1 in. long Celanese GY-70 fibers impregnated with proprietary epoxy resin; exposed to seven-day aging at 400 K; zero rebulking observed; test panels were cut from them at 450 K and 1000 psi; cured for 1.5 hr followed by 2 hr post cure at 450 K; fiber content 48.2 volume %; density 1.64 g cm ⁻³ ; measurements parallel to fibers.
100	Keller, L. B. and Raech, H.	1974	L			Similar to the above specimen; measurements perpendicular to fibers.
101	Goggin, W. R.	1974	L	278-313		Composite from Goodyear Corp. of Akron, Ohio; six plies made of Thornel 75S graphite fibers embedded in ELNB/4617 epoxy resin; nominal composition 37 weight % resin; measurements parallel (in plane) to the fiber orientation.
102	Goggin, W. R.	1974	L	278-313		The above specimen except measurements after exposure to 77 K.
103*	Goggin, W. R.	1974	L	278-313		Similar to the above specimen except measurements perpendicular to laminate.
104*	Goggin, W. R.	1974	L	278-313		Similar to the above specimen except Modmor 1 graphite fibers used; measurements parallel (in plane) to the fiber orientation.
105*	Goggin, W. R.	1974	L	278-313		The above specimen except measurements after exposure to 77 K; no further changes observed after six additional cycles.
106*	Goggin, W. R.	1974	L	278-313		Similar to the above specimen except measurements perpendicular to laminate plane.
107*	Hertz, J., Christian, J. L., and Varian, M.	1972	L	80-450	NO568	Courtaude HTS/Faberite X-904; expansion for unidirectional lay up in 0 deg direction.
108*	Hertz, J., et al.	1972	L	80-450	NO602	Similar to the above specimen and conditions.
109*	Hertz, J., et al.	1972	L	78-450	Specimen No. 684	Similar to the above specimen and conditions; panel 1A-39-1.
110*	Hertz, J., et al.	1972	L	78-450	Specimen No. 685	Similar to the above specimen and conditions; last stable cycle.
111*	Hertz, J., et al.	1972	L	89-450	Specimen No. 715	Similar to the above specimen and condition; specimen water boiled for 24 hr.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
112*	Hertz, J., Christian, J. L., and Varlas, M.	1972	L	79-450	Specimen No. 716	Similar to the above specimen and conditions.
113*	Hertz, J., et al.	1972	L	79-450	NO566	Similar to the one from Curve 107; expansion for unidirectional layup in 90 deg direction; zero-point correction 0.013%.
114*	Hertz, J., et al.	1972	L	79-450	NO567	Similar to the above specimen and conditions; zero-point correction 0.01%.
115*	Hertz, J., et al.	1972	L	78-450	Specimen No. 692	Similar to the above specimen and conditions; panel 1A-39-1; zero-point correction 0.028%.
116*	Hertz, J., et al.	1972	L	76-450	Specimen No. 693	Similar to the above specimen and conditions; zero-point correction 0.02%.
117*	Hertz, J., et al.	1972	L	78-450	Specimen No. 720	Similar to the above specimen and conditions; last stable cycle; zero-point correction 0.04%.
118*	Hertz, J., et al.	1972	L	78-450	Specimen No. 718	Similar to the above specimen and conditions; zero-point correction 0.02%.
119*	Hertz, J., et al.	1972	L	86-455	NO530	Similar to the above specimen; expansion for $[\pm 45^\circ]_c$ layup in 0 deg direction; zero-point correction 0.003%.
120*	Hertz, J., et al.	1972	L	84-457	NO531	Similar to the above specimen and conditions; panel OC16-C5; zero-point correction 0.001%.
121*	Hertz, J., et al.	1972	L	84-456	NO537	Similar to the above specimen, expansion for $[\pm 45^\circ]_c$ layup in 45 deg direction.
122	Hertz, J., et al.	1972	L	84-452	NO536	Similar to the above specimen and conditions; zero-point correction 0.002%.
123*	Hertz, J., et al.	1972	L	81-450	NO569	Similar to the above specimen and conditions; expansion for $[\pm 45^\circ]_s$ in the 0 deg direction.
124*	Hertz, J., et al.	1972	L	81-450	NO570	Similar to the above specimen and conditions.
125*	Hertz, J., et al.	1972	L	80-444	NO571	Similar to the above specimen and conditions; expansion for $[\pm 45^\circ]_s$ in the 90 deg direction; zero-point correction 0.005%.
126*	Hertz, J., et al.	1972	L	80-444	NO572	Similar to the above specimen and conditions.
127*	Hertz, J., et al.	1972	L	79-450	NO573	Chinese GY-70/Faberite X-904; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.002%.
128*	Hertz, J., et al.	1972	L	79-450	NO579	Similar to the above specimen and conditions; zero-point correction -0.001%.
129*	Hertz, J., et al.	1972	L	80-450	NO575	Similar to the above specimen and conditions; expansion in the 90 deg direction; zero-point correction 0.022%.
130*	Hertz, J., et al.	1972	L	79-446	NO577	Similar to the above specimen and conditions; zero-point correction 0.034%.
131*	Hertz, J., et al.	1972	L	78-450	NO587	Similar to the above specimen and conditions; expansion for $[\pm 45^\circ]_c$ lay up in the 45 deg direction.
132*	Hertz, J., et al.	1972	L	79-449	NO588	Similar to the above specimen and conditions; zero-point correction -0.001%.
133*	Hertz, J., et al.	1972	L	79-449	NO590	Similar to the above specimen and conditions; expansion in 0 deg direction.
134*	Hertz, J., et al.	1972	L	79-452	NO591	Similar to the above specimen and conditions.
135*	Hertz, J., et al.	1972	L	131-450	NO593	Similar to the above specimen and conditions; expansion for $[\pm 45^\circ]_s$ in 0 deg direction.

* Not shown in figure.

TABLE 7-8. MEASUREMENT INFORMATION ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

Cur. Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
136*	Hertz, J., Christian, J. L., and Varian, M.	1972	L	76-450	NO597	Similar to the above specimen and conditions.
137*	Hertz, J., et al.	1972	L	74-448	NO599	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.001%.
138*	Hertz, J., et al.	1972	L	76-446	NO600	Similar to the above specimen and conditions; zero-point correction 0.002%.
139*	Hertz, J., et al.	1972	L	83-451	NO538	Celanese GY-70/Courtaulds HM-S/Faberite X-904; panel OC15-L-CC2; expansion for unidirectional lay up in 0 deg direction.
140*	Hertz, J., et al.	1972	L	83-450	NO539	Similar to the above specimen and conditions.
141*	Hertz, J., et al.	1972	L	80-451	NO565	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.002%.
142*	Hertz, J., et al.	1972	L	80-408	NO540	Similar to the above specimen and conditions; zero-point correction -0.001%.
143*	Hertz, J., et al.	1972	L	78-450	Specimen No. 709	Similar to the above specimen and conditions; panel 70-HMS-E-2, Batch 1A-13; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.001%.
144*	Hertz, J., et al.	1972	L	78-450	Specimen No. 710	Similar to the above specimen and conditions.
145*	Hertz, J., et al.	1972	L	78-450	Specimen No. 712	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.02%.
146*	Hertz, J., et al.	1972	L	77-450	Specimen No. 713	Similar to the above specimen and conditions; zero-point correction 0.001%.
147*	Hertz, J., et al.	1972	L	78-450	Specimen No. 724	Similar to the above specimen and conditions; specimen water boiled for 24 hr; expansion for unidirectional lay up in 0 deg direction; zero-point correction -0.003%.
148*	Hertz, J., et al.	1972	L	89-450	Specimen No. 729	Similar to the above specimen and conditions; zero-point correction -0.001%.
149*	Hertz, J., et al.	1972	L	78-448	Specimen No. 726	Similar to the above specimen and conditions; expansion in 90 deg direction; zero-point correction 0.007%.
150*	Hertz, J., et al.	1972	L	78-450	Specimen No. 727	Similar to the above specimen and conditions; zero-point correction 0.002%.
151*	Hertz, J., et al.	1972	L	80-450	NO630	Good Year random molded HT-S/X-904 laminate; expansion in 0 deg direction.
152*	Hertz, J., et al.	1972	L	79-453	NO634	Similar to the above specimen and conditions; zero-point correction -0.001%.
153*	Hertz, J., et al.	1972	L	80-451	NO632	Similar to the above specimen; expansion in 30 deg direction; zero-point correction 0.01%.
154*	Hertz, J., et al.	1972	L	76-451	NO631	Similar to the above specimen and conditions; zero-point correction 0.005%.

* Not shown in figure.

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 1*													
293	0.000	290	0.00008	360	0.268	410	0.519	360	0.225	310	0.061	CURVE 14 (cont.)	
323	0.008	293	0.00000	373	0.328	423	0.594	372	0.277	323	0.102		
CURVE 2*													
298	-0.00009	395	0.384	435	0.674	435	0.305	379	0.305	335	0.149		
310	-0.0005	398	0.446	448	0.752	448	0.752	385	0.323	348	0.189		
317	-0.0008	410	0.504	CURVE 10									
323	-0.0012	423	0.553	447	0.801	404	0.327	399	0.332	360	0.231		
335	-0.0023	431	0.575	435	0.734	400	0.338	395	0.338	373	0.269		
348	-0.0033	435	0.590	423	0.652	404	0.312	400	0.338	385	0.319		
353	-0.0037	441	0.597	410	0.601	435	0.734	404	0.327	398	0.368		
360	-0.0042	445	0.601	423	0.652	435	0.734	408	0.312	410	0.428		
366	-0.0044	448	0.601	410	0.570	410	0.570	413	0.377	423	0.470		
373	-0.0046	452	0.596	398	0.485	415	0.251	415	0.377	429	0.545		
385	-0.0048	454	0.571	385	0.410	417	0.242	417	0.242	435	0.596		
390	-0.0049	373	0.345	373	0.345	418	0.240	418	0.240	448	0.688		
CURVE 5													
398	-0.0052	360	0.292	360	0.292	423	0.236	423	0.236	CURVE 15			
410	-0.0060	348	0.244	348	0.244	426	0.236	426	0.236	448	0.703		
423	-0.0070	335	0.198	335	0.198	431	0.246	431	0.246	443	0.642		
435	-0.0075	323	0.153	323	0.153	436	0.260	436	0.260	435	0.573		
445	-0.0087	310	0.089	310	0.089	441	0.284	441	0.284	431	0.537		
CURVE 6													
448	-0.004	448	0.781	308	0.070	293	0.000	447	0.320	423	0.482		
373	-0.004	423	0.688	293	0.000	CURVE 13							
385	-0.005	435	0.613	CURVE 11									
398	-0.006	410	0.541	293	0.0000	445	0.796	445	0.796	398	0.358		
410	-0.007	398	0.474	306	0.0005	443	0.746	443	0.746	385	0.313		
423	-0.008	385	0.408	308	0.0006	435	0.654	435	0.654	373	0.263		
435	-0.009	373	0.344	310	0.0006	427	0.606	427	0.606	360	0.218		
445	-0.010	360	0.293	362	0.0022	423	0.586	423	0.586	348	0.181		
CURVE 4													
445	-0.006	323	0.135	362	0.0022	410	0.469	410	0.469	335	0.147		
435	-0.006	310	0.083	363	0.0022	400	0.388	400	0.388	323	0.104		
423	-0.006	298	0.028	365	0.0023	398	0.371	398	0.371	310	0.064		
410	-0.005	295	0.011	416	0.0041	385	0.314	385	0.314	297	0.018		
398	-0.005	293	0.000	417	0.0041	373	0.265	373	0.265	293	0.000		
373	-0.005	298	0.0002	419	0.0042	360	0.228	360	0.228	293	0.0000		
367	-0.005	293	0.00000	348	0.185	348	0.185	348	0.185	305	-0.0006		
360	-0.004	288	0.00002	335	0.143	335	0.143	335	0.143	307	-0.0007		
CURVE 7													
360	-0.004	310	0.062	323	0.105	293	0.000	323	0.099	309	-0.0008		
348	-0.003	335	0.013	297	0.013	306	0.035	310	0.057	361	-0.0066		
335	-0.002	348	0.204	306	0.035	312	0.052	297	0.014	363	-0.0068		
323	-0.001	360	0.255	312	0.052	323	0.091	323	0.000	416	-0.0142		
317	-0.001	373	0.310	323	0.310	335	0.135	418	0.014	418	-0.0144		
310	0.000	385	0.374	385	0.374	398	0.447	420	0.000	420	-0.0146		
298	0.000	398	0.447	398	0.447	293	0.000	445	0.000	445	-0.0171		
293	0.000	300	0.026	300	0.026	297	0.014	297	0.014	449	-0.0172		
323	0.000	310	0.105	323	0.105	348	0.179	348	0.179				
310	0.000	335	0.152	335	0.152								
297	0.013	348	0.204	348	0.204								
310	0.062	360	0.255	360	0.255								
323	0.106	373	0.310	373	0.310								
335	0.156	385	0.374	385	0.374								
348	0.211	398	0.447	398	0.447								

* Not shown in figure.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 17*		CURVE 21*		CURVE 25*		CURVE 29*		CURVE 33*	
293	0.0000	423	0.0064	423	0.0057	293	0.0000	293	0.0000
307	0.0010	410	0.0059	410	0.0051	298	0.0003	298	0.0002
308	0.0011	398	0.0053	398	0.0047	310	0.0010	310	0.0008
310	0.0012	373	0.0042	373	0.0037	323	0.0015	323	0.0014
362	0.0048	348	0.0032	348	0.0027	335	0.0020	335	0.0020
363	0.0049	335	0.0026	335	0.0022	348	0.0025	348	0.0026
365	0.0050	323	0.0021	323	0.0018	373	0.0035	373	0.0038
417	0.0087	310	0.0015	310	0.0012	398	0.0045	398	0.0051
419	0.0088	298	0.0006	298	0.0004	410	0.0050	410	0.0057
420	0.0089	293	0.0000	293	0.0000	424	0.0065	423	0.0063
CURVE 18		CURVE 22*		CURVE 26		CURVE 30*		CURVE 34	
293	0.0000	293	0.0000	293	0.0000	424	0.0050	293	0.0000
298	0.0003	298	0.0002	298	0.0003	410	0.0045	298	0.0002
310	0.0009	310	0.0007	310	0.0008	398	0.0040	310	0.0003
323	0.0016	323	0.0010	323	0.0012	373	0.0031	323	-0.0004
335	0.0023	335	0.0014	335	0.0016	348	0.0022	335	-0.0011
348	0.0029	348	0.0017	348	0.0021	335	0.0017	348	-0.0021
373	0.0043	373	0.0023	373	0.0029	323	0.0013	360	-0.0030
398	0.0056	398	0.0030	398	0.0038	310	0.0008	373	-0.0041
410	0.0063	410	0.0033	410	0.0043	298	0.0002	385	-0.0051
420	0.0068	423	0.0036	423	0.0048	293	0.0000	398	-0.0063
CURVE 19		CURVE 23*		CURVE 27*		CURVE 31*		CURVE 35	
420	0.0063	423	0.0002	293	0.0000	293	0.0000	410	-0.0108
410	0.0057	410	-0.0001	398	0.0003	298	0.0002	398	-0.0096
398	0.0051	398	-0.0003	310	0.0008	310	0.0008	385	-0.0083
373	0.0038	373	-0.0007	323	0.0014	323	0.0013	373	-0.0071
348	0.0025	348	-0.0008	335	0.0018	335	0.0018	360	-0.0058
335	0.0018	335	-0.0008	348	0.0024	348	0.0024	348	-0.0045
323	0.0012	323	-0.0007	373	0.0034	373	0.0034	335	-0.0032
310	0.0006	310	-0.0006	398	0.0044	398	0.0055	323	-0.0018
298	0.0001	298	-0.0002	410	0.0049	410	0.0050	310	-0.0003
293	0.0000	293	0.0000	421	0.0053	424	0.0056	298	0.0002
CURVE 20		CURVE 24*		CURVE 28*		CURVE 32*		CURVE 36	
293	0.0000	293	0.0000	421	0.0043	424	0.0053	353	0.0000
298	0.0002	298	0.0003	410	0.0039	410	0.0047	393	0.043
310	0.0008	310	0.0008	398	0.0034	398	0.0041	CURVE 42*, †	
323	0.0013	323	0.0012	373	0.0025	373	0.0030	298	0.011
335	0.0018	335	0.0016	348	0.0017	348	0.0020	310	0.038
348	0.0023	348	0.0021	335	0.0012	335	0.0015	323	0.072
373	0.0033	373	0.0031	323	0.0009	323	0.0010	335	0.106
398	0.0044	398	0.0040	310	0.0005	310	0.0005	348	0.145
410	0.0049	410	0.0045	298	0.0002	298	0.0001	360	0.183
423	0.0055	423	0.0050	293	0.0000	293	0.0000	373	0.225
CURVE 37		CURVE 38*, †		CURVE 39*, †		CURVE 40*, †		CURVE 41*, †	
410	0.405	353	0.000	353	0.000	353	0.000	353	0.000
407	0.392	393	-0.005	393	-0.005	393	0.019	393	0.019
402	0.372	CURVE 39*, †		CURVE 40*, †		CURVE 41*, †		CURVE 42*, †	
398	0.356	353	0.000	353	0.000	353	0.000	353	0.000
385	0.305	393	0.000	393	0.000	393	0.000	393	0.077

* Not shown in figure.

† This curve is here reported using the first given temperature as reference temperature at which $\Delta L/L_0 = 0$.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 43*,†		CURVE 53*		CURVE 61*		CURVE 67 (cont.)*		CURVE 72	
353	0.000	243	-0.101	243	-0.180	142	-0.0037	77	-0.376
303	0.149	293	0.000	293	0.000	172	-0.0036	131	-0.305
		303	0.020	303	0.036	200	-0.0024	172	-0.236
CURVE 44*,†		CURVE 54*		CURVE 62*		227	-0.0024	214	-0.167
353	0.000	243	-0.082	243	-0.133	255	-0.0007	254	-0.090
303	0.231	293	0.000	293	0.000	293	0.0000	297	0.001
CURVE 45*,†		303	0.016	303	0.027	331	0.0002	337	0.103
353	0.0000	CURVE 55*		CURVE 63*		365	0.0011	366	0.173
303	-0.0004	243	-0.061	243	-0.111	CURVE 68		407	0.301
CURVE 46*,†		293	0.000	293	0.000	77	-0.463	448	0.449
353	0.0000	303	0.012	303	0.022	297	0.019	CURVE 73	
303	-0.0052	CURVE 56*		CURVE 64*		450	0.785	77	-0.392
CURVE 47*,†		243	-0.132	243	-0.233	CURVE 69		131	-0.317
353	0.0000	293	0.000	293	0.000	79	0.0059	172	-0.249
303	0.0242	303	0.026	303	0.047	131	0.0052	212	-0.178
CURVE 48*,†		CURVE 57*		CURVE 65		173	0.0044	255	-0.090
353	0.0000	243	-0.096	243	-0.132	215	0.0036	337	0.103
303	0.0474	293	0.000	293	0.000	256	0.0011	366	0.174
CURVE 49*,†		303	0.020	303	0.020	297	-0.0001	407	0.301
353	0.0000	CURVE 58*		CURVE 66		448	0.449	CURVE 74	
303	0.1162	243	-0.067	243	-0.067	77	-0.401	77	-0.0271
CURVE 50*,†		293	0.000	293	0.000	131	-0.317	130	-0.0212
353	0.0000	303	0.013	303	0.013	172	-0.249	171	-0.0160
303	0.2008	CURVE 59*		CURVE 70		212	-0.178	212	-0.0110
CURVE 51*,†		243	-0.067	243	-0.067	255	0.090	252	-0.0059
353	0.0000	293	0.000	293	0.000	337	0.103	293	0.0000
303	0.2456	303	0.013	303	0.013	366	0.174	338	0.0084
CURVE 52*		CURVE 60*		CURVE 71*		407	0.301	364	0.0148
243	-0.128	243	-0.244	243	-0.428	448	0.449	406	0.0273
293	0.000	293	0.000*	297	0.011	CURVE 75*		450	0.0409
303	0.026	303	0.049	560	0.763	200	-0.215	CURVE 76*	
CURVE 53*		CURVE 67*		CURVE 72*		224	-0.166	77	-0.0364
243	-0.128	243	-0.244	243	-0.428	250	-0.111	129	-0.0277
293	0.000	293	0.000*	297	0.011	289	-0.018	171	-0.0217
303	0.026	303	0.049	560	0.763	346	0.128	214	-0.0152
CURVE 54*		CURVE 73*		CURVE 74*		370	0.203	252	-0.0076
243	-0.128	243	-0.244	243	-0.428	384	0.245	293	0.0000
293	0.000	293	0.000*	297	0.011	405	0.328	338	0.0082
303	0.026	303	0.049	560	0.763	411	0.349	365	0.0147
CURVE 55*		CURVE 75*		CURVE 76*		425	0.404	406	0.0273
243	-0.128	243	-0.244	243	-0.428	434	0.430	450	0.0407
293	0.000	293	0.000*	297	0.011	CURVE 77*		CURVE 78*	
303	0.026	303	0.049	560	0.763	77	-0.392	77	-0.074
CURVE 56*		CURVE 77*		CURVE 78*		131	-0.317	297	0.002
243	-0.128	243	-0.244	243	-0.428	172	-0.249	450	0.045
293	0.000	293	0.000*	297	0.011	212	-0.178	CURVE 79*	
303	0.026	303	0.049	560	0.763	255	0.090	77	-0.0388
CURVE 57*		CURVE 79*		CURVE 80*		337	0.103	297	-0.0012
243	-0.128	243	-0.244	243	-0.428	366	0.174	450	-0.0504
293	0.000	293	0.000*	297	0.011	407	0.301	CURVE 81*	
303	0.026	303	0.049	560	0.763	448	0.449	77	-0.0345
CURVE 58*		CURVE 80*		CURVE 81*		CURVE 82*		130	-0.0268
243	-0.128	243	-0.244	243	-0.428	200	-0.215	172	-0.0198
293	0.000	293	0.000*	297	0.011	224	-0.166	214	-0.0140
303	0.026	303	0.049	560	0.763	250	-0.111	253	-0.0096
CURVE 59*		CURVE 81*		CURVE 82*		289	-0.018	339	0.0071
243	-0.128	243	-0.244	243	-0.428	346	0.128	366	0.0131
293	0.000	293	0.000*	297	0.011	370	0.203	407	0.0233
303	0.026	303	0.049	560	0.763	384	0.245	425	0.404
CURVE 60*		CURVE 82*		CURVE 83*		405	0.328	434	0.430
243	-0.128	243	-0.244	243	-0.428	411	0.349	CURVE 84*	
293	0.000	293	0.000*	297	0.011	425	0.404	77	-0.0388
303	0.026	303	0.049	560	0.763	434	0.430	297	-0.0012
CURVE 61*		CURVE 83*		CURVE 84*		CURVE 85*		450	-0.0504
243	-0.128	243	-0.244	243	-0.428	200	-0.215	CURVE 86*	
293	0.000	293	0.000*	297	0.011	224	-0.166	77	-0.0364
303	0.026	303	0.049	560	0.763	250	-0.111	129	-0.0277
CURVE 62*		CURVE 84*		CURVE 85*		289	-0.018	171	-0.0217
243	-0.128	243	-0.244	243	-0.428	346	0.128	214	-0.0152
293	0.000	293	0.000*	297	0.011	370	0.203	252	-0.0076
303	0.026	303	0.049	560	0.763	384	0.245	293	0.0000
CURVE 63*		CURVE 85*		CURVE 86*		405	0.328	338	0.0082
243	-0.128	243	-0.244	243	-0.428	411	0.349	365	0.0147
293	0.000	293	0.000*	297	0.011	425	0.404	406	0.0273
303	0.026	303	0.049	560	0.763	434	0.430	450	0.0407

* Not shown in figure.

† This curve is here reported using the first given temperature as reference temperature at which $\Delta L/L_0 = 0$.

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 81*		CURVE 87		CURVE 92*		CURVE 94 (cont.)*		CURVE 97 (cont.)*	
77	-0.218	79	-0.0094	ξ		150	-0.392	300.2	0.0001
297	0.007	132	-0.0106	CURVE 93*		161	-0.366	339.0	0.0001
450	0.291	174	-0.0081	95	-0.257	172	-0.340	CURVE 98*	
CURVE 82		216	-0.0060	106	-0.247	183	-0.314	255.4	-0.099
77	0.0094	257	-0.0034	115	-0.238	193	-0.290	268.5	-0.170
129	0.0085	297	0.0003	126	-0.227	201	-0.270	269.7	-0.170
171	0.0079	340	0.0034	135	-0.217	210	-0.223	296.0	0.010
212	0.0055	369	0.0061	146	-0.205	225	-0.206	299.7	0.030
255	0.0036	409	0.0114	156	-0.193	234	-0.179	300.7	0.030
339	-0.0038	451	0.0214	167	-0.179	242	-0.155	339.2	0.209
368	-0.0078	CURVE 88*		177	-0.167	255	-0.115	CURVE 99*	
410	-0.0097	76	-0.0197	188	-0.153	264	-0.088	239	-0.0049
448	-0.0099	131	-0.0168	198	-0.140	293	0.000	277	-0.0014
CURVE 83*		172	-0.0134	207	-0.128	300	0.023	311	0.060
77	-0.450	214	-0.0084	215	-0.116	319	0.089	277	-0.0014
297	0.013	256	-0.0045	225	-0.102	323	0.103	311	0.0016
450	0.517	293	0.0000	234	-0.089	332	0.137	344	0.0046
CURVE 84		339	0.0060	246	-0.072	347	0.199	CURVE 100	
75	0.0121	365	0.0101	255	-0.058	355	0.236	239	-0.213
129	0.0107	409	0.0199	265	-0.043	372	0.322	277	-0.059
169	0.0085	451	0.0263	293	0.000	373	0.361	311	0.067
213	0.0047	CURVE 89*		299	0.009	389	0.424	344	0.175
255	0.0020	79	-0.0205	309	0.026	CURVE 95		CURVE 101	
293	0.0000	131	-0.0171	316	0.038	255.2	-0.0005	278	0.0002
341	-0.0011	171	-0.0129	319	0.043	269.7	-0.0005	313	-0.0003
366	-0.0017	215	-0.0101	326	0.056	298.0	0.0002	CURVE 102*	
413	-0.0025	255	-0.0051	329	0.062	298.6	0.0002	278	0.0005
457	-0.0028	293	0.0000	338	0.080	299.4	0.0002	313	-0.0006
CURVE 85		340	0.0055	347	0.099	339.0	0.0017	CURVE 103*	
453	-0.0034	367	0.0079	356	0.120	CURVE 96*		278	0.0008
467	-0.0032	409	0.0172	358	0.125	255.4	-0.0008	174	0.0024
340	0.0018	CURVE 90		370	0.157	268.7	-0.0004	215	0.0022
298	0.0000	77	0.0109	376	0.175	273.2	-0.0004	255	0.0008
75	0.0122	560	-0.0185	382	0.195	299.2	0.0001	298	0.0000
CURVE 86*		CURVE 91		394	0.240	300.7	0.0001	339	-0.0006
77	-0.523	77	-0.517	401	0.271	339.2	0.0002	370	-0.0006
297	0.006	297	0.014	CURVE 94*		CURVE 97*		409	0.0023
450	0.585	560	1.000	81	-0.529	255.4	-0.0004	450	0.0058
CURVE 87*		CURVE 91		92	-0.510	268.7	-0.0004	CURVE 110*	
77	-0.523	77	-0.517	100	-0.495	273.2	-0.0004	278	-0.0016
297	0.006	297	0.014	109	-0.478	299.2	0.0001	313	0.0022
450	0.585	560	1.000	120	-0.457	CURVE 97*		CURVE 111*	
CURVE 88*		CURVE 91		130	-0.436	255.4	-0.0004	78	0.0023
75	0.0122	CURVE 91		140	-0.414	268.7	-0.0004	133	0.0023
453	-0.0034	77	-0.517	CURVE 94*		299.2	0.0001	174	0.0024
367	0.0026	297	0.014	81	-0.529	CURVE 97*		215	0.0022
340	0.0018	560	1.000	92	-0.510	255.4	-0.0004	255	0.0008
75	0.0122	CURVE 91		100	-0.495	268.7	-0.0004	298	0.0000
CURVE 89*		CURVE 91		109	-0.478	273.2	-0.0004	339	-0.0006
77	-0.523	77	-0.517	120	-0.457	299.2	0.0001	370	-0.0006
297	0.006	297	0.014	130	-0.436	CURVE 97*		409	0.0023
450	0.585	560	1.000	140	-0.414	255.4	-0.0004	450	0.0058
CURVE 90*		CURVE 91		81	-0.529	268.7	-0.0004	CURVE 112*	
75	0.0122	CURVE 91		92	-0.510	273.2	-0.0004	78	0.0023
453	-0.0034	77	-0.517	100	-0.495	299.2	0.0001	133	0.0023
367	0.0026	297	0.014	109	-0.478	CURVE 97*		174	0.0024
340	0.0018	560	1.000	120	-0.457	255.4	-0.0004	215	0.0022
75	0.0122	CURVE 91		130	-0.436	268.7	-0.0004	255	0.0008
CURVE 91*		CURVE 91		140	-0.414	299.2	0.0001	298	0.0000
77	-0.523	77	-0.517	CURVE 94*		CURVE 97*		339	-0.0006
297	0.006	297	0.014	81	-0.529	255.4	-0.0004	370	-0.0006
450	0.585	560	1.000	92	-0.510	268.7	-0.0004	409	0.0023
CURVE 92*		CURVE 91		100	-0.495	273.2	-0.0004	450	0.0058
77	-0.523	77	-0.517	109	-0.478	CURVE 97*		CURVE 113*	
297	0.006	297	0.014	120	-0.457	255.4	-0.0004	278	-0.0016
450	0.585	560	1.000	130	-0.436	268.7	-0.0004	313	0.0022
CURVE 93*		CURVE 91		140	-0.414	299.2	0.0001	CURVE 114*	
75	0.0122	CURVE 91		81	-0.529	255.4	-0.0004	78	0.0023
453	-0.0034	77	-0.517	92	-0.510	268.7	-0.0004	133	0.0023
367	0.0026	297	0.014	100	-0.495	273.2	-0.0004	174	0.0024
340	0.0018	560	1.000	109	-0.478	299.2	0.0001	215	0.0022
75	0.0122	CURVE 91		120	-0.457	CURVE 97*		255	0.0008
CURVE 94*		CURVE 91		130	-0.436	255.4	-0.0004	298	0.0000
77	-0.523	77	-0.517	140	-0.414	268.7	-0.0004	339	-0.0006
297	0.006	297	0.014	CURVE 94*		299.2	0.0001	370	-0.0006
450	0.585	560	1.000	81	-0.529	CURVE 97*		409	0.0023
CURVE 95*		CURVE 91		92	-0.510	255.4	-0.0004	450	0.0058
75	0.0121	CURVE 91		100	-0.495	268.7	-0.0004	CURVE 115*	
129	0.0107	77	-0.517	109	-0.478	CURVE 97*		78	0.0023
169	0.0085	297	0.014	120	-0.457	255.4	-0.0004	131	0.0016
213	0.0047	560	1.000	130	-0.436	268.7	-0.0004	174	0.0016
255	0.0020	CURVE 91		140	-0.414	299.2	0.0001	215	0.0016
293	0.0000	CURVE 91		81	-0.529	CURVE 97*		256	0.0016
341	-0.0011	CURVE 91		92	-0.510	255.2	-0.0005	300	-0.0001
366	-0.0017	CURVE 91		100	-0.495	269.7	-0.0005	366	-0.0024
413	-0.0025	CURVE 91		109	-0.478	298.0	0.0002	410	-0.0028
457	-0.0028	CURVE 91		120	-0.457	298.6	0.0002	450	-0.0035
CURVE 85		CURVE 91		130	-0.436	299.4	0.0002	CURVE 109*	
453	-0.0034	CURVE 91		140	-0.414	339.0	0.0017	239	-0.213
467	-0.0032	CURVE 91		81	-0.529	CURVE 96*		277	-0.059
340	0.0018	CURVE 91		92	-0.510	255.2	-0.0005	311	0.067
298	0.0000	CURVE 91		100	-0.495	269.7	-0.0005	344	0.175
75	0.0122	CURVE 91		109	-0.478	298.0	0.0002	CURVE 101	
CURVE 86*		CURVE 91		120	-0.457	298.6	0.0002	278	0.0002
77	-0.523	CURVE 91		130	-0.436	299.4	0.0002	313	-0.0003
297	0.006	CURVE 91		140	-0.414	339.0	0.0017	CURVE 102*	
450	0.585	CURVE 91		81	-0.529	CURVE 96*		278	0.0005
CURVE 87*		CURVE 91		92	-0.510	255.4	-0.0008	313	-0.0006
75	0.0122	CURVE 91		100	-0.495	268.7	-0.0004	CURVE 103*	
453	-0.0034	CURVE 91		109	-0.478	273.2	-0.0004	278	-0.078
367	0.0026	CURVE 91		120	-0.457	299.2	0.0001	313	0.104
340	0.0018	CURVE 91		130	-0.436	300.7	0.0001	CURVE 104*	
298	0.0000	CURVE 91		140	-0.414	339.2	0.0002	278	-0.0016
75	0.0122	CURVE 91		81	-0.529	CURVE 97*		313	0.0022
CURVE 88*		CURVE 91		92	-0.510	255.4	-0.0008	CURVE 110*	
77	-0.523	CURVE 91		100	-0.495	268.7	-0.0004	278	-0.0016
297	0.006	CURVE 91		109	-0.478	273.2	-0.0004	313	0.0022
450	0.585	CURVE 91		120	-0.457	299.2	0.0001	CURVE 111*	
CURVE 89*		CURVE 91		130	-0.436	300.7	0.0001	78	0.0023
75	0.0122	CURVE 91		140	-0.414	339.2	0.0002	133	0.0023
453	-0.0034	CURVE 91		81	-0.529	CURVE 97*		174	0.0024
367	0.0026	CURVE 91		92	-0.510	255.4	-0.0008	215	0.0022
340	0.0018	CURVE 91		100	-0.495	268.7	-0.0004	255	0.0008
298	0.0000	CURVE 91		109	-0.478	273.2	-0.0004	298	0.0000
75	0.0122	CURVE 91		120	-0.457	299.2	0.0001	339	-0.0006
CURVE 90*		CURVE 91		130	-0.436	300.7	0.0001	370	-0.0006
77	-0.523	CURVE 91		140	-0.414	CURVE 97*		409	0.0023
297	0.006	CURVE 91		81	-0.529	255.4	-0.0008	450	0.0058
450	0.585	CURVE 91		92	-0.510	268.7	-0.0004	CURVE 112*	
CURVE 91*		CURVE 91		100	-0.495	273.2	-0.0004	78	0.0023
77	-0.523	CURVE 91		109	-0.478	299.2	0.0001	133	0.0023
297	0.006	CURVE 91		120	-0.457	CURVE 97*		174	0.0024
450	0.585	CURVE 91		130	-0.436	255.4	-0.0008	215	0.0022
CURVE 92*		CURVE 91		140	-0.414	268.7	-0.0004	255	0.0008
75	0.0122	CURVE 91		81	-0.529	273.2	-0.0004	298	0.0000
453	-0.0034	CURVE 91		92	-0.510	299.2	0.0001	339	-0.0006
367	0.0026	CURVE 91		100	-0.495	300.7	0.0001	370	-0.0006
340	0.0018	CURVE 91		109	-0.478	CURVE 97*		409	0.0023
298	0.0000	CURVE 91		120	-0.457	3			

TABLE 7-9. EXPERIMENTAL DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER EPOXY COMPOSITE (continued)

T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$	T	$\Delta L/L_0$
CURVE 110 (cont.)*		CURVE 114*		CURVE 118*		CURVE 122*		CURVE 126*	
215	0.0006	79	-0.4386	78	-0.605	84	-0.0515	80	-0.175
255	0.0002	130	-0.3464	130	-0.504	132	-0.0401	130	-0.141
298	0.0000	171	-0.2790	172	-0.402	174	-0.0303	174	-0.109
340	-0.0007	213	-0.2041	214	-0.284	217	-0.0214	216	-0.076
366	-0.0018	255	-0.0966	255	-0.154	258	-0.0114	255	-0.042
409	-0.0028	298	0.0119	297	0.020	336	0.0094	299	0.006
450	0.0014	338	0.1474	339	0.171	370	0.0159	340	0.056
CURVE 111*		365	0.2464	408	0.279	411	0.0281	366	0.091
89	0.0031	407	0.4100	408	0.453	452	0.0406	409	0.145
131	0.0043	450	0.5831	450	0.657	CURVE 123*		444	0.208
173	0.0025	CURVE 115*		CURVE 119*		CURVE 127*		CURVE 131*	
215	0.0024	78	-0.472	86	-0.0712	81	0.0080	78	-0.0036
255	0.0012	131	-0.396	133	-0.0590	132	0.0069	130	-0.0026
299	0.0000	171	-0.308	174	-0.0460	173	0.0068	173	-0.0020
340	-0.0012	214	-0.207	217	-0.0335	215	0.0048	229	-0.0025
366	-0.0015	255	-0.094	258	-0.0165	255	0.0029	258	-0.0014
409	-0.0007	298	0.015	301	-0.0006	298	0.0000	302	0.0001
450	0.0015	339	0.154	336	0.0147	339	-0.0022	340	0.0025
CURVE 112*		366	0.259	370	0.0294	366	-0.0038	368	0.0047
79	0.0023	409	0.435	412	0.0483	407	-0.0064	409	0.0069
130	0.0024	450	0.625	455	0.0673	450	-0.0095	450	0.0094
171	0.0036	CURVE 116*		CURVE 120*		CURVE 124*		CURVE 132*	
214	0.0016	76	-0.521	84	-0.0240	81	0.0010	79	0.0150
255	0.0007	131	-0.421	131	-0.0169	130	0.0013	131	0.0122
297	0.0000	172	-0.337	176	-0.0126	171	0.0020	174	0.0092
338	-0.0002	214	-0.229	216	-0.0082	212	0.0008	214	0.0060
367	0.0000	255	-0.111	257	-0.0043	254	0.0001	255	0.0023
407	0.0005	297	0.014	300	0.0010	296	0.0000	299	-0.0005
450	0.0023	339	0.159	334	0.0060	336	-0.0011	339	-0.0046
CURVE 113*		366	0.266	369	0.0091	364	-0.0019	367	-0.0066
79	-0.4430	409	0.435	411	0.0125	406	-0.0041	409	-0.0094
130	-0.3574	450	0.635	457	0.0179	450	-0.0067	449	-0.0120
171	-0.2760	CURVE 117*		CURVE 121*		CURVE 125*		CURVE 133*	
213	-0.2060	78	-0.534	84	-0.0223	80	-0.169	79	0.0190
255	-0.1067	130	-0.423	131	-0.0171	130	-0.134	131	0.0145
298	0.0149	172	-0.341	173	-0.0117	173	-0.104	174	0.0115
338	0.1424	214	-0.226	215	-0.0060	216	-0.071	214	0.0090
365	0.2459	255	-0.108	257	-0.0039	255	-0.035	255	0.0041
407	0.4130	297	0.040	300	0.0000	299	0.006	299	0.0000
450	0.5859	339	0.188	334	0.0042	340	0.050	339	-0.0042
* Not shown in figure.		366	0.284	369	0.0066	366	0.083	367	-0.0059
		408	0.462	411	0.0109	409	0.132	409	-0.0085
		450	0.674	456	0.0146	444	0.172	449	-0.0113

e. Thermal Diffusivity

There are no experimental data available for the thermal diffusivity of graphite fiber epoxy composites.

In view of the difficulty of establishing the recommended values for the thermal conductivity, and of the fact that the thermal diffusivity of a composite is not a well-defined quantity, the calculation of the thermal diffusivity from specific heat, thermal conductivity, and density values has not been carried out.

4. REFERENCES

1. Lyman, T. (Editor), Metals Handbook, Vol. 1, American Society for Metals, Metals Park, Ohio, 1300 pp., 1961.
2. Alcoa, Alcoa Aluminum Handbook, Aluminum Company of America, Pittsburgh, Pennsylvania, 222 pp., 1959.
3. The Aluminum Association, Aluminum Standards and Data, The Aluminum Association, New York, 174 pp., 1968.
4. Powell, R. L., Hall, W. J., and Roder, H. M., "Low Temperature Transport Properties of Commercial Metals and Alloys. II. Aluminums," *J. Appl. Phys.*, 31(3), 496-503, 1960.
5. Zavaritskii, N. V. and Zeldovich, A. G., "Thermal Conductivity of Technical Materials at Low Temperatures," *Sov. Phys.-Tech. Phys.*, 1(9), 1970-4, 1956.
6. Lucks, C. F., Thompson, H. B., Smith, A. R., Curry, F. P., Deem, H. W., and Bing, G. F., "The Experimental Measurement of Thermal Conductivities, Specific Heats, and Densities of Metallic, Transparent, and Protective Materials. Part I," U.S. Air Force Rept. USAF TR-6145, 127 pp., 1951.
7. Evans, J. E., Jr., "Thermal Conductivity of 14 Metals and Alloys Up to 1100 F (595 C)," Nat. Advis. Committee, Aeronautics, Res. Memo E50L07, 15 pp., 1951.
8. Ho, C. Y., Ackerman, M. W., Wu, K. Y., Oh, S. G., and Havill, T. N., "Thermal Conductivity of Ten Selected Binary Alloy Systems" Purdue University, CINDAS-TPRC Rept. 30, 230 pp., 1975; in course of publication in the *Journal of Physical and Chemical Reference Data*.
9. Powers, R. W., Ziegler, J. B., and Johnston, H. L., "The Thermal Conductivity of Metals and Alloys at Low Temperatures. III. Data for Aluminum Alloys Between 25 and 300 K," U.S. Air Force Rept. USAF TR-264-7, 13 pp., 1951.
10. Rhodes, B. L., Moeller, C. E., and Sauer, H. J., "Apparatus for Determining Thermal Conductivity of Solids from 20 to 600 K," *Cryogenics*, 5(1), 17-20, 1965.
11. Garth, R. C. and Sailer, V. L., "Thermal Conductivity of Graphite," Brookhaven National Laboratory Rept. BNL-69, 19 pp., 1949.
12. Williams, D. R., "The Thermal Conductivities of Several Metals. An Evaluation of a Method Employed by the Bureau of Standards," Southern Methodist University, M.S. Thesis, 96 pp., 1966. [NASA-CR-82479]

13. Williams, D.R. and Blum, H.A., "The Thermal Conductivities of Several Metals. An Evaluation of a Method Employed by the National Bureau of Standards," in Proceedings of the Seventh Conference on Thermal Conductivity, Gaithersburgh, Maryland (1967), 349-54, 1968.
14. Smuda, P.A., Fletcher, L.S., and Gyorog, D.A., "Heat Transfer Between Surfaces in Contact. The Effect of Low Conductance Interstitial Materials. Part 1. Experimental Verification of NASA Test Apparatus," NASA-CR-73122, 112 pp., 1967. [N67-37212]
15. Clausing, A.M., "Thermal Contact Resistance in a Vacuum Environment," University of Illinois at Urbana, Ph.D. Thesis, 156 pp., 1963.
16. Abbott, R.E., "Experimental Facilities for Investigating Thermal Contact Conductance in a Vacuum Environment," Arizona State University, M.S. Thesis, 157 pp., 1967.
17. Makarounis, O. and Jenkins, R.J., "Thermal Diffusivity and Heat Capacity Measurements at Low Temperatures by the Flash Method," Naval Radiological Defense Lab. Rept. USNRDL-TR-599, 16 pp., 1962. [AD295 885]
18. Suzuki, T., "The Nature of Preston-Guinier Atom-Groups in an Age-Hardened Aluminum-Copper Alloy. I - Experimental. II - Theoretical," Sci. Rep. Research Tohoku Univ., A1(3), 189-92, 1949.
19. Hultgren, R., Desai, P.D., Hawkins, D.T., Gleiser, M., Kelley, K.K., and Wagman, D.D., Selected Values of the Thermodynamic Properties of the Elements, American Society for Metals, Metals Park, Ohio, 636 pp., 1973.
20. Lucks, C.F. and Deem, H.W., "Thermal Properties of Thirteen Metals", American Society for Testing Materials, Special Technical Publication No. 227, 30 pp., 1958.
21. Lucks, C.F., Matolich, J., and Vanvelzor, J.A., "The Experimental Measurement of Thermal Conductivities, Specific Heats, and Densities of Metallic, Transparent, and Protective Materials. Part III," U.S. Air Force Rept. AF-TR-6145, 71 pp., 1954. [AD954 06]
22. Schattyn, J.M., "Thermal Property Data Utilized for Asset Materials," McDonnell Aircraft Corp. Rept. A656, 45 pp., 1964. [AD480 414]
23. Makarounis, O., "Solar Absorptance and Total Hemispherical Emittance Measurements," U.S. Air Force Rept. AFML-TR-66 43, 25 pp., 1966. [AD489 653L]

24. Dietz, J. L., "Thermal Properties of Selected Metals. Report on Field Artillery Guided Missile System Redstone," Chrysler Corp., Missile Division, Technical Memo MT-M15, 23 pp., 1956. [AD 289 577]
25. Zoller, P. and Dillinger, J. R., "Low-Temperature Specific Heat (1.6 to 4 K) of Six Commercial Aluminum Alloys," Rev. Sci. Instrum., 40(6), 776-7, 1969.
26. Makarounis, O., "Heat Capacity by the Radiant Energy Absorption Technique," Thermophysics of Spacecraft and Planetary Bodies, Prog. Astronaut. Aeronaut., 20, 203-18, 1967.
27. Touloukian, Y. S. (Editor), "Recommended Values of the Thermophysical Properties of Eight Alloys, Major Constituents and Their Oxides," TPRC Technical Rept. No. 16, 540 pp., 1966.
28. Clark, A. F., "Low Temperature Thermal Expansion of Some Metallic Alloys," Cryogenics, 8(5), 282-9, 1968.
29. Arp, V., Wilson, J. H., Winrich, L., and Sikora, P., "Thermal Expansion of Some Engineering Materials from 20 to 293 K," Cryogenics, 2, 230-5, 1962.
30. Valentich, J., "New Values for Thermal Coefficients," Product Engineering, 63-71, 1965.
31. Hidnert, P. and Krider, H. S., "Thermal Expansion of Aluminum and Some Aluminum Alloys," J. Res. Natl. Bur. Stds., 48(3), 209-19, 1952.
32. Willey, L. A. and Fink, W. L., "An Interferometer Type of Dilatometer, and Some Typical Results," Trans. Am. Inst. Mining Met. Engrs., 162, 642-55, 1945.
33. Hertz, J., "An Evaluation of the Mechanical Properties of Adhesives at Cryogenic Temperatures and Their Correlation with Molecular Structure," General Dynamics/Astronautics Rept. GDA-ERR-AN-196, 54 pp., 1962. [AD 831 537]
34. NASA, "Technical Support Package for Technical Brief 69-10055-Thermal Expansion Properties of Aerospace Materials," NASA Technology Utilization Division, 174 pp., 1969. [PB 184 749]
35. Belov, A. K., "Expansion Coefficients of Structural Materials at Low Temperatures," Metal Science Heat Treatment Metals (4), 267-9, 1968.
36. Butler, C. P. and Inn, E. C. Y., "Thermal Diffusivity of Metals at Elevated Temperatures," U.S. Naval Radiological Defense Lab. Tech. Rept. USNRDL-TR-177, 27 pp., 1957. [AD 143 863]

37. Butler, C. P. and Inn, E. C. Y., "Thermal Diffusivity of Metals at Elevated Temperatures," ASME Symp. Thermal Prop., 377-90, 1959.
38. Tomsic, M., "The Temperature Wave Method of Measuring Thermal Diffusivity and Thermal Contact Conductance," Kansas State University, M.S. Thesis, 170 pp., 1969.
39. Cushman, J. B., Jr., "Determination of the Thermal Diffusivity of Metals Using a Modified Jominy End Quench Test," University of Washington, M.S. Thesis, 48 pp., 1964.
40. Stutins, W. and Dillinger, J. R., "Magnetic and Thermal Properties of Some Austenitic Stainless Steels at Low Temperatures," J. Appl. Phys., 44(6), 2887-8, 1973.
41. Powers, R. W., Ziegler, J. B., and Johnston, H. L., "The Thermal Conductivity of Metals and Alloys at Low Temperatures. II. Data on Iron and Several Steels between 25 and 300 K. Influence of Alloying Constituents," U.S. Air Force Rept. USAF TR-264-6, 14 pp., 1951.
42. Moeller, E., "Guarded Double-Cylinder Apparatus for Determining Thermal Conductivities from 80 to 860 K," in Proceedings of the 8th Thermal Conductivity Conference, Plenum Press, New York, 701-11, 1969.
43. Deverall, J. E., "The Thermal Conductivity of a Molten Pu-Fe Eutectic (9.5 at/o Fe)," Los Alamos Scientific Lab. Rept. LA-2269, 62 pp., 1959.
44. Taylor, R. E., Powell, R. W., Naibantyan, M., and Davis, F., "Evaluation of Direct Electrical Heating Methods for the Determination of Thermal Conductivity at Elevated Temperatures," U.S. Air Force Rept. AFML-TR-68-227, 74 pp., 1968.
45. Moeller, C. E. and Finch, H. L., "Transparent Boundary Apparatus for Determining Heat Flow Through Glass," Proc. 4th Thermal Conductivity Conference, VII-A-1 to 16, 1964.
46. Tye, R. P., Hayden, R. W., and Spinney, S. C., "The Thermal Conductivity of a Number of Alloys at Elevated Temperatures," High Temp.-High Pressures, 4(5), 503-11, 1972.
47. Ho, C. Y., Ackerman, M. W., Wu, K. Y., Oh, S. G., and Havill, T. N., "Electrical Resistivity of Ten Selected Binary Alloy Systems," Purdue University, CINDAS Report to NBS, in preparation.

48. Ewing, C. T., Grand, J. A., and Miller, R. R., "Thermal Conductivity of Liquid Sodium and Potassium," *J. Am. Chem. Soc.*, 74, 11-4, 1952.
49. Brophy, J. H. and Sinnott, M. J., "The Thermal and Electrical Conductivities of Ductile Cast-Iron and Several Gray Cast Irons," *Trans. Am. Soc. Metals*, 52, 567-81, 1960.
50. Smith, C. F., "Apparatus for Determining Low Temperature Thermal Conductivity," NASA-TM-X-50852, 31 pp., 1963. [N63-23040]
51. Feith, A. D., Hein, R. A., Johnstone, C. P., and Flagella, P. N., "Thermophysical Properties of Low Carbon 304 Stainless Steel to 1350 C," in Proceedings of the 8th Thermal Conductivity Conference, Plenum Press, New York, 1051-65, 1969.
52. Feith, A. D., Hein, R. A., Johnstone, C. P., and Flagella, P. N., "Thermophysical Properties of Low-Carbon 304 Stainless Steel to 1350 C," USAEC Rept. GEMP-643, 14 pp., 1968; *Nucl. Sci. Abstr.*, 23(6), 10187, 1969.
53. Nalbantyan, M., "Determination of Thermal Conductivity at High Temperatures by Direct Electrical Heating Methods," Purdue University, M. S. Thesis, 109 pp., 1968.
54. Brown, W. T., Jr. and Bergles, A. E., "Measurement of Thermal Conductivity for Electrically Heated Heat-Transfer Test Sections," *Proc. 4th Symp. Thermophys. Prop.*, 184-8, 1968.
55. Tye, R. P., "An Experimental Investigation of the Thermal Conductivity and Electrical Resistivity of Three Porous 304L Stainless Steel 'Rigimesh' Materials to 1300 K," NASA-CR-72710, 23 pp., 1970.
56. Tye, R. P., "The Thermal and Electrical Conductivities of Porous Copper and Stainless Steel to Elevated Temperatures," ASME-73-HT-47, 8 pp., 1973.
57. Bondi, P. and Ferro, V., "Thermal Conductivity Measuring Apparatus for Metals," *Termotecnica (Milan)*, 21(6), 298-303, 1967.
58. Careaga, J. A., Mayer, E. R., and Del Castillo, L., "System for Thermal Conductivity Measurements in Solids at 65-300 K," *Rev. Mex. Fis.*, 19, FA68-76, 1970.
59. Conway, J. B. and Flagella, P. N., "Physical and Mechanical Properties of Reactor Materials," USAEC Rept. GEMP-1012(Pt. 1), 13-70, 1969.

60. Lyusternik, V. E., "The Measurement of the True Thermal Capacity of Heat-Resisting Steels," *Phys. Metals Metallog.* (USSR), 7(3), 40-3, 1959.
61. Neel, D. S., Pears, C. D., and Oglesby, S., Jr., "The Thermal Properties of Thirteen Solid Materials to 5000° F or Their Destruction Temperatures," U.S. Air Force Rept. WADD-TR-60-924, 216 pp., 1962. [AD275 536]
62. Smith, R. H., "The Measurement of the Thermal Diffusivity, Specific Heat, and Thermal Conductivity by a Flash Technique," University of Kansas, M.S. Thesis, 1964.
63. Venuti, R. and Seibel, R. D., "High Temperature Thermophysical Properties," Denver Research Institute Rept. DRI-1023, 1959.
64. Zoller, P., Decker, P. R., and Dillinger, J. R., "Anomalous Low-Temperature Specific Heat of Austenitic Stainless Steels," *J. Appl. Phys.*, 40(4), 1964-6, 1969.
65. Conway, J. B. and Flagella, P. N., "Physicochemical Studies of Clad UO₂ Under Reactor Accident Conditions," General Electric Co., Missile and Space Div. Progress Rept. 76, 229-51, 1968. [N69-38826]
66. Furman, D. E., "Thermal Expansion Characteristics of Stainless Steels between -300° and 1000° F," *Trans. Met. Soc. AIME*, 188, 688-91, 1950.
67. Yaggee, F. L., Gilbert, E. R., and Styles, J. W., "Thermal Expansivities, Thermal Conductivities, and Densities of Vanadium, Titanium, Chromium, and Some Vanadium-Base Alloys," *J. Less-Common Metals*, 19(1), 39-51, 1969.
68. Beenakker, J. J. M. and Swenson, C. A., "Total Thermal Contractions of Some Technical Metals to 4.2° K," *Rev. Sci. Instr.*, 26, 1204-5, 1955.
69. Martin, W. R. and Weir, J. R., "Dimensional Behavior of the Experimental Gas-Cooled Reactor Fuel Element at Elevated Temperatures," Oak Ridge National Lab. Rept. ORNL-3103, 48 pp., 1961.
70. Droege, J. W., "Volumetric Expansion of Silver Alloy," Battelle Memorial Institute Rept. TID-26251, 5 pp., 1972.
71. Jenkins, R. J. and Westover, R. W., "The Thermal Diffusivity of Stainless Steel Over the Temperature Range 20-1000 C," U.S. Air Force Rept. USNRDL-TR-484, 13 pp., 1960. [AD249 578]
72. Jenkins, R. J. and Parker, W. J., "A Flash Method for Determining Thermal Diffusivity Over a Wide Temperature Range," U.S. Air Force Rept. Rept. WADD-TR-61-95, 27 pp., 1961. [AD268752]

73. Jenkins, R. J. and Westover, R. W., "Thermal Diffusivity of Stainless Steel from 20 to 1000 Degrees," *J. Chem. Eng. Data*, 7, 434-7, 1962.
74. Conway, J. B. and Flagella, P. N., "Physical and Mechanical Properties of Reactor Materials," USAEC Rept. GEMP-1004, 14-88, 1968.
75. Kandrach, G. S., Private Communication, Corning Glass Works, Feb. 17, 1975.
76. Flynn, D. R., "Thermal Conductivity of Semiconductive Solids, Method for Steady-State Measurements on Small Disk Reference Samples," *Nat. Bur. Std. Rept.* 7740, 41 pp., 1962. [AD411157]
77. Robinson, H. E. and Flynn, D. R., "The Current Status of Thermal Conductivity Reference Standards at the National Bureau of Standards," *Natl. Bur. Std. Rept.* NBS-R-8300, 14 pp., 1964. [AD439619L]
78. Chang, G. K. and Jones, R. E., "Low Temperature Thermal Conductivity of Amorphous Solids," *Phys. Rev.*, 126, 2055-8, 1962.
79. Rudkin, R. L., "Thermal Diffusivity Measurements on Metals and Ceramics at High Temperatures," U.S. Air Force Rept. ASD-TDR-62-24 (Part 2), 16 pp., 1963. [AD413005]
80. Flynn, D. R. and Robinson, H. E., "The National Bureau of Standards High-Temperature Cut-Bar Apparatus for Determination of the Thermal Conductivity of Small Solids," *Natl. Bur. Std. Rept.* 8301, 38 pp., 1964. [AD486355]
81. Braman, R. S., "Methods of Purification of Metals and Intermetallic Compounds," U.S. Air Force Rept. WADD-TR-59-303-Pt-3, 48 pp., 1962. [AD802970]
82. Bienert, W. B., Trimmer, D. S., and Skrabek, E. A., "Technique for Measuring Thermal Conductivity of Thermoelectric Materials," *Proc. IEEE/AIAA Thermoelec. Spec. Conf.*, 6.1-7, 1966.
83. Bienert, W. B., Trimmer, D. S., and Skrabek, E. A., "Technique for Measuring Thermal Conductivity of T/E Materials," *Proc. Conf. AIAA Thermophys. Spec.*, No. 6, 1-10, 1966.
84. Flynn, D. R., Robinson, H. E., and Martz, I. L., "Present Status of Pyroceram Code 9606 as a Thermal Conductivity Reference Standard," *Proc. 4th Thermal Cond. Conf.*, Part 4, 1-28, 1964.
85. Peggs, I. D. and Mills, R. W., "The Direct Determination of Thermal Conductivity by the Flash Technique," *Rev. Int. Hautes Temp. Refract.*, 7(3), 264-7, 1970.

86. Corning Glass Works, Materials Handbook, Corning Glass Works, Corning, New York, Vol. 1, 1958.
87. Rudkin, R. L., "Thermal Diffusivity Measurements on Ceramics at High Temperatures," Proc. 3rd Conf. Thermal Cond., 794-808, 1963.
88. Plummer, W.A., Campbell, D. E., and Comstock, A. A., "Method of Measurement of Thermal Diffusivity to 1000 Degrees," J. Am. Ceram. Soc., 45, 310-6, 1962.
89. Gibby, R. L., "The Thermal Diffusivity and the Thermal Conductivity of Stoichiometric $(U_{0.8}Pu_{0.2})O_2$," Pacific Northwestern Lab. Rept. BNWL-704, 39 pp., 1968.
90. Flieger, H.W., Jr., "The Thermal Diffusivity of Pyroceram at High Temperatures," Proc. 3rd Thermal Cond. Conf., 769-83, 1963.
91. Plummer, W.A., "A Thermal Diffusivity Measurement Technique," Proc. 3rd Thermal Cond. Conf., 809-28, 1963.
92. Ruddlesden, S. N. and Popper, P., "The Preparation, Properties and Structure of Silicon Nitride," Trans. British Ceramic Soc., 60, 603-26, 1961.
93. Rabenau, A., "Silicon Nitride, A Ceramic for High Temperature," Ber. Deut. Keram. Ges., 40, 6-12, 1963.
94. Powell, R.W. and Tye, R. P., "Thermal and Electrical Conductivities of Some Metallic Compounds," Proceedings of the 8th Thermal Conductivity Conference, Plenum Press, New York, 575-83, 1969.
95. Godfrey, D.J. and Lindley, M.W., "Engineering Ceramics," Engr. Ceram. Prog. Rep. 12/72, 49 pp., 1972. [AD908471]
96. Wells, W.M., "Silicon Nitride as a High-Temperature Random Material," University of California, Lawrence Radiation Lab. Rept. UCRL-7795 Conf-633-1, 16 pp., 1964.
97. Moeller, C. E. and Wilson, D. R., "Determination of the Thermal Properties of Materials at Elevated Temperatures," Midwest Research Institute Rept. MRI-2059-E, 95 pp., 1960.
98. Neel, D.S. and Pears, C.D., "High Temperature Thermal Property Measurement to 5000 F," Proc. 2nd Symp. Thermophys. Prop., 500-11, 1962.

99. Powell, R.W. and Tye, R. P., "Thermal Conductivity of Ceramic Materials and Measurements with a New Form of Thermal Comparator," Sp. Ceram. Proc. Symp. Brit. Ceram. Res. Assoc., 261-80, 1963.
100. Powell, R.W., "The Use of Thermal Comparator Methods for the Measurement of Thermal Conductivity," Proc. Black Hills Summer Conf. on Transport Phenomenon, 95-154, 1962. [AD 289 290]
101. Swarts, E. I. and Crandall, W. B., "Fundamental Properties of Metal-Ceramics Mixtures at High Temperatures," New York State College of Ceramics, Alfred Univ., 71 pp., 1955. [AD 769 56]
102. Lange, F. F., "The Si_3N_4 -SiC Composite System: Effect of Microstructure on Strength," Westinghouse Res. Lab. Materials Sci. Dept., 45 pp., 1972. [AD 743 510]
103. Kelley, K. K., "Data on Theoretical Metallurgy. X. High-Temperature Heat Content, Heat Capacity, and Entropy Data for Inorganic Compounds," U.S. Bureau of Mines, Bulletin 476, 241 pp., 1949.
104. Satoh, S., "The Heat of Formation and Specific Heat of Silicon Nitride," Sci. Papers Inst. Phys. Chem. Research (Tokyo), 34, 144-54, 1938; Bull. Chem. Soc. Japan, B, 41-8, 1938.
105. McLean, A. F., Fisher, E. A., and Bratton, R. J., "Brittle Materials Design, High Temperature Gas Turbine," Army Materials and Mechanics Research Center Rept. AMMRC-CTR-73-32, 226 pp., 1973.
106. Pehlke, R. D. and Elliott, J. F., "High-Temperature Thermodynamics of the Silicon, Nitrogen, Silicon-Nitride System," Trans. Met. Soc. AIME, 215, 781-5, 1959.
107. Washburn, M. E., "Silicon Oxynitride Refractories," Bull. Am. Ceram. Soc., 46(7), 667-71, 1967.
108. Stull, D. R. and Prophet, H., "JANAF Thermochemical Tables, Second Edition," National Bureau of Standards Rept. NSRDS-NBS-37, 1123 pp., 1971.
109. Tokuyama, T., Fujii, Y., Sugita, Y., and Kishino, S., "Thermal Expansion Coefficient of a Pyrolytically Deposited Silicon Nitride Film," J. Appl. Phys., 6(10), 1252-3, 1967.
110. Burkhardt, P. J. and Marvel, R. F., "Thermal Expansion of Sputtered Silicon Nitride Films," J. Electrochem. Soc., 116(6), 864-6, 1969.

111. Gregor, L.V., "A Dielectric Material for Study of Silicon Nitride as Microelectronic Applications," Wright-Patterson Air Force Base, Air Force Avionics Lab. Rept. AFAL-TR-68-272, 34 pp., 1968. [AD 843 876]
112. Steele, S.R., Pappis, J., Schilling, H., and Hagan, L., "Chemical Vapor Deposited Materials for Electron Tubes," U.S. Army Electronics Command Progress Rept. 15 November 1966-14 February 1967, 57 pp., 1967. [AD651 021]
113. Thompson, D.S. and Pratt, P.L., "Structure of Silicon Nitride," Sci. Ceram., 6(13), 33-51, 1965.
114. Iwai, S. and Yasunaga, A., "Thermal Expansion of Silicon Nitride Si_3N_4 ," Naturwissenschaften, 46(15), 473-4, 1959.
115. Carr, E.M. and Bartlett, R.W., "Evaluation of Duplex Whisker - Crystalline Silicon Nitride Structures," U.S. Air Force Rept. AFML-TR-68-197, 70 pp., 1968. [AD 840 593]
116. Gille, J.P., "Development of Advanced Materials for Integrated Tank Insulation System for the Long Term Storage of Cryogenics in Space, NASA-CR-102570, 171 pp., 1969.
117. Hertz, J., Christian, J.L., and Varlas, M., "Advanced Composite Applications for Spacecraft and Missile," U.S. Air Force Rept. AFML-TR-71-186-Vol. 2, 394 pp., 1972. [AD 893 715L]
118. Kim, D.H., "The Thermophysical Properties of Fiber Reinforced Plastics," American Institute of Aeronautics and Astronautics, AIAA Paper No. 72-366, AIAA/ASME/SAE 13th Structures, Structural Dynamics, and Materials Conf., 9 pp., 1972.
119. Nakamura, H.H. and Larsen, D.C., "Thermal Expansion Behavior of Boron-Epoxy and Graphite-Epoxy Advanced Composite Materials," Amer. Inst. Phys., Conf. Proc., 17, 117-28, 1974.
120. Haskins, J.F., Campbell, M.D., Hertz, J., and Percy, J.L., "Thermophysical Properties of Plastic Materials and Composites to Liquid Hydrogen Temperature (-423 F)," General Dynamics/Astronautics Rept. ML-TDR-64-33(Pt. 1), 179 pp., 1964. [AD601 337]
121. Campbell, M.D., Haskins, J.F., O'Barr, G.L., and Hertz, J., "Thermophysical Properties of Reinforced Plastics at Cryogenic Temperatures," J. Spacecr. Rockets, 3(4), 596-9, 1966.

122. Haskins, J. F., Percy, J. L., Campbell, M. D., and Hertz, J., "The Determination of Thermophysical Properties of Plastic Materials and Composites at Cryogenic Temperatures," Wright-Patterson Air Force Base, Application Lab. Rept. BVJ-63-001-5, 50 pp., 1963.
123. Baltakis, F. P., Hurd, D. E., and Holmes, R. F., "Effects of High Temperature, High Velocity Gases on Plastic Materials," U.S. Air Force Rept. WADC-TR-59-459, 34 pp., 1960.
124. Engelke, W. T., Pears, C. D., and Oglesby, S., Jr., "The Thermophysical Properties of Plastic Materials from -50 F to Over 700 F," U.S. Air Force Rept. ASTIA-5783-1399-IX, 40 pp., 1963.
125. Southern Research Institute, "The Thermophysical Properties of Plastic Materials from -50 F to Over 700 F," U.S. Air Force Rept. ASTIA-6366-1399-XV, 114 pp., 1963.
126. Pears, C. D., Engelke, W. T., and Thornburgh, J. D., "The Thermophysical Properties of Plastic Materials from -50 F to Over 700 F. Part I," Southern Research Institute Rept. ML-TDR-64-87, Pt. 1, 260 pp., 1964.
127. Gray, C. O., "Resume of Thermal Property Data from Twenty-Four Potential Re-Entry Insulation Materials," Army Missile Command, Redstone Arsenal Rept. DSN-TN-6-58, 44 pp., 1958.
128. Lewis, W., "Thermal Conductivity-Temperature Relationship for Nine Glass and Asbestos Fiber-Reinforced Aircraft Plastics," U.S. Forest Service Research Paper RN-FPL-36, 15 pp., 1965. [AD470 821]
129. Toth, L. W., "Properties of Glass-Reinforced Epoxy Through the 20 K Range," *Mod. Plastics*, 42(12), 123-28, 130, 1965.
130. Toth, L. W., Boller, T. J., Butcher, I. R., Karlotis, A. H., and Yoder, F. D., "Program for the Evaluation of Structural Reinforced Plastic Materials at Cryogenic Temperatures," NASA-CR-80061, 239 pp., 1966.
131. Avco Corporation, "Evaluation of the Thermal Properties of Materials," NASA-CR-65980, 208 pp., 1966.
132. Ogawa, K. and Noguchi, Y., "The Measurement of Thermal Properties of Reinforced Plastics at Temperatures Up to 150 C (Infrared Radiation Method)," National Aeronautics Lab., Tokyo, Japan Rept. NAL-TR-150, 23 pp., 1968. [N68-36636]

133. Lagedrost, J. F., Fabish, T. J., Eldridge, E. A., Deem, H. W., Krause, H. H., and Vaughan, D. A., "Thermal Conductivity," in Thermophysical Characterization of Charring Ablative Materials. Final Report, NASA-CR-73399, 13-18, 1968. [N70-14131]
134. Campbell, M. D., Hertz, J., O'Barr, G. L., and Haskins, J. F., "Thermophysical Properties of Plastic Materials and Composites to Liquid Hydrogen Temperature (-423°F)," General Dynamics/Astronautics Rept. ML-TDR-64-33, Pt. 2, 37 pp., 1965.
135. Kirillov, V. N., Avrasin, Ya. D., Efimov, V. A., and Dobrokhotova, R. A., "Influence of the Conditions of Heat Treatment of Glass-Reinforced Plastics on Their Thermal Properties," Sov. Plast., (2), 66-8, 1973.
136. Kirillov, V. N., Avrasin, Ya. D., Efimov, V. A., and Dobrokhotova, R. A., "Effect of a Heat Treatment of Glass-Reinforced Plastics on Their Thermophysical Properties," Plast. Massy, (2), 58-60, 1973.
137. Melonas, J. V., Covington, P. C., and Pears, C. D., "Measurement of the Thermal Properties of Various Aircraft Structural Materials," U.S. Air Force Rept. WADC-TR-58-179, 55 pp., 1958. [AD204795]
138. Campbell, M. D., O'Barr, G. L., Haskins, J. F., and Hertz, J., "Thermophysical Properties of Plastic Materials and Composites to Liquid Hydrogen Temperature (-423°F)," U.S. Air Force Rept. TDR-64-33-Pt. 3, 88 pp., 1965. [AD468155]
139. Gulati, S. T. and Plummer, W. A., "Thermal Expansion of Ribbon-Reinforced Composites," Amer. Inst. Phys. Conf. Proc., (3), 257-68, 1972.
140. Kritsuk, A. A., "Coefficients of Thermal Expansion of Glass-Reinforced Plastics and Their Components at Low and High Temperatures," Probl. Proch., 4(5), 98-102, 1972.
141. Kritsuk, A. A., "Thermal Expansion Coefficients of Some Glass-Reinforced Plastics and Their Components at Low and High Temperatures," Strength Mater., 4(5), 611-15, 1972.
142. General Electric Co., "Hollow Glass Fiber Reinforced Laminates," General Electric Co., Space Sciences Lab. Final Rept., 142 pp., 1964. [AD451684]
143. Brechna, H. and Haldemann, W., "Physical Properties of Filament Wound Glass Epoxy Structures as Applied to Possible Use in Liquid Hydrogen Bubble Chambers," Stanford Linear Accelerator Center Rept., 47 pp., 1965. [N66-25109]

144. Soffer, L. M. and Molho, R., "Mechanical Properties of Epoxy Resins and Glass/Epoxy Composites at Cryogenic Temperatures," Proceedings of the NASA-CASE Conf. Properties of Polymers at Cryogenic Temperatures, Cleveland, Ohio (1967), 87-117, 1968.
145. Kalnin, I. L., "Thermal Expansion of High Modulus Graphite Fiber/Epoxy Composites," Proc. Ann. Conf. Reinf. Plast. Compos. Inst. Soc. Plast. Ind., 29(21C), 8 pp., 1974.
146. Knibbs, R. H., Baker, D. J., and Rhodes, G., "Thermal and Electrical Properties of Carbon-Fiber Unidirectional Reinforced Epoxy Composites," Proc. 26th Ann. Conf. Soc. Plast. Ind., 1-10, 1971.
147. Leidler, H. R., Krikorian, O. H., and Young, D. A., "Thermodynamic Properties of Carbon Up to Critical Point," Carbon, 11, 555-63, 1973.
148. Freeman, W. T. and Campbell, M. D., "Thermal Expansion Characteristics of Graphite-Reinforced Composite Materials," Amer. Soc. Test., Spec. Tech. Publ. STP497, 121-42, 1972.
149. Knibbs, R. H. and Morris, J. B., "The Effects of Fibre Orientation on the Physical Properties of Carbon Fiber-Epoxy Resin Composites," Atomic Energy Research Establishment, Harwell, Berks, England, Rept. AERE-R-6926, 37 pp., 1971.
150. Goggin, W. R., "Thermomechanical Stability of Graphite/Epoxy Composites," Appl. Opt., 13(2), 444-50, 1974.
151. Freund, N. P., "Advanced Composite Missile and Space Design Data," U.S. Air Force Rept. AFML-TR-74-33, 73 pp., 1974. [AD 919 165L]
152. Prime, R. B., Barrall, E. M., II, Logan, J. A., and Duke, P. J., "Thermal Expansion Measurement in the Plane of Thin Fiber-Reinforced Composites," Amer. Inst. Phys. Conf. Proc., (17), 72-84, 1974.
153. Dauksys, R. J., "Graphite Fiber and Boron Nitride Fiber Filled Potting Compounds," U.S. Air Force Rept. AFML-TR-73-101, 36 pp., 1973.
154. Pirgon, O., Wostenholm, G. H., and Yates, B., "Thermal Expansion at Elevated Temperatures. IV. Carbon-Fiber Composites," J. Phys. D, 6(3), 309-21, 1973.
155. Keller, L. B. and Raech, H., "Manufacturing Methods for Dimensionally Stable Composite Microwave Components," U.S. Air Force Rept. AFML-TR-74-70, 574 pp., 1974. [AD 920 253L]

156. Koh, J.C.Y. and Fortini, A., "Prediction of Thermal Conductivity and Electrical Resistivity of Porous Metallic Materials," J. Heat Mass Transfer, 16, 2013-2022, 1973.